TRENDS IN CLIMATE AND URBANIZATION AND THEIR IMPACTS ON SURFACE WATER SUPPLY IN THE CITY OF ADDIS ABABA, ETHIOPIA

by

BISRAT KIFLE ARSISO

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SUPERVISOR: PROF G H STOFFBERG

CO-SUPERVISOR: PROF G M TSIDU

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DECLARATION

I, **Bisrat Kilfe Arsiso**, hereby declare that this thesis entitled: **"Trends in Climate and Urbanization and Their Impacts on Surface Water Supply in the City of Addis Ababa, Ethiopia**," which I submit for the degree of Doctor of Philosophy in Environmental Management at the University of South Africa, is my own work and has not previously been submitted by me for a degree at this or any other institution.

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SIGNED Date

....

Name: Bisrat Kifle Arsiso

Student number: 53407946

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ABSTRACT

Understanding climate change and variability at urban scale is essential for water resource management, land use planning, and development of adaption plans. However, there are serious challenges to meet these goals due to unavailability of observed and / or simulated high resolution spatial and temporal climate data. Recent efforts made possible the availability of high resolution climate data from non-hydrostatic regional climate model (RCM) and statistically downscaled General Circulation Models (GCMs). This study investigates trends in climate and urbanization and their impact on surface water supply for the city of Addis Ababa, Ethiopia.

The methodology presented in this study focused on the observed and projected NIMR-HadGEM2-AO model and Special Report on Emissions Scenarios (SRES) of B2 and A2 of HadCM3 model are also employed for rainfall, maximum temperature and minimum temperature data using for climate analysis. Water Evaluation and Planning (WEAP) modeling system was used for determination of climate and urbanization impacts on water. Land-Sat images were analyzed using Normalized Differencing Vegetation Index (NDVI). Statistical downscaling model (SDSM) was employed to investigate the major changes and intensity of the urban heat island (UHI). The result indicates monthly rainfall anomalies with respect to the baseline mean showing wet anomaly in summer (kiremt) during 2030s and 2050s, and a dry anomaly in the 2080s under A2 and B2 scenarios with exception of a wet anomaly in September over the city. The maximum temperature anomalies under Representative Concentration Pathways (RCPs) also show warming during near, mid and end terms. The mean monthly minimum temperature anomalies under A2 and B2 scenarios are warm but the anomalies are much lower than RCPs. The climate under the RCP 8.5 and high population growth (3.3 %) scenario will lead to the unmet demand of 462.77 million m^3 by 2039. Future projection of urban heat island under emission pathway of A2 and B2 scenario shows that, the nocturnal UHI will be intense in winter or dry season episodes in the city. Under A2 scenario the highest urban warming will occur during October to December (2.5 ºC to 3.2 ºC). Under RCP 8.5 scenario the highest urban warming will occur during October to December (0.5 ºC to 1.0 °C) in the 2050s and 2080s. Future management and adaptation strategies are to expand water supply to meet future demand and to implement demand side water management systems of the city and UHI.

Keywords: *Climate Change; Representative Concentration Pathways (RCPs); NIMR-HadGEM2-AO; General Circulation Models (GCMs);Normalized Differencing Vegetation Index (NDVI); Urban Heat Island (UHI); Water Evaluation and Planning (WEAP); adaptation strategies.*

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LIST OF ACRONYMS AND ABBREVIATIONS

AABoFED	Addis Ababa Bureau of Finance and Economic Development
AABIAS	Addis Ababa Bole-International Airport Station
AACPPO	Addis Ababa City Planning Project Office
AAOBS	Addis Ababa Observatory Station
AAWSA	Addis Ababa Water and Sewerage Authority
ACMAD-MESA	African Centre of Meteorological Applications for Development–Monitoring for Environment and Security Agency
AOGCM	Atmosphere–Ocean General Circulation Model
AR4	Forth Assessment Report
AR5	Fifth Assessment Report
AU	African Union
CLINO	Climatological normal (1961-1990)
CLUVA	Climate Change and Urban Vulnerability in Africa
CMIP3	Coupled Model Inter-comparison Project Three
CMIP5	Coupled Model Inter-comparison Project Five
CRU	Climatic Research Unit
CSA	Central Statistic Authority
DN	Diameter Nominal (in mm)
EEA	Ethiopian Economics Association
ENSO	El Niño Southern Oscillation
ENVI	Environment for Visualizing Images (software)

EROS	Earth Resources Observation and Science
ESMF	Earth System Modeling Framework
ETB	Ethiopian Birr
FAO	Food and Agricultural Organization
FDRE	Federal Democratic Republic of Ethiopia
FMAM	February, March, April and May
GCM	Global Circulation Models
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamics Laboratory
GHGs	Greenhouse gases
GIS	Geographic Information System
GPCC	Global Precipitation Climatology Centre
GRID	Global Resource Information Database
GTP	Growth and Transformation Plan
HadCM3	Hadley Centre model version 3 (UK Met Office's)
HadGEM2-AO	Hadley Centre Global Environmental Model version 2 Atmosphere-Ocean (AO) configuration (UK Met Office's)
IAMs	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
IUWM	Integrated urban water management
JJAS	June, July, August and September
LCCP	London Climate Change Partnership

LUH	Land-use Harmonization
MCM	Million Cubic Meter
MESP	Ministry of Environment and Spatial Planning
MLR	Multiple linear regression
MoFED	Ministry of Finance and Economic Development
MoH	Ministry of Health
MoUDHC	Ministry of Urban Development, Housing and Construction
MoWEI	Ministry of Water, Energy and Irrigation
MoWR	Ministry of Water Resource
NASA	National Aeronautical and Space Administration (United States)
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NIMR	National Institute of Meteorological Research
NIR	Near Infra Red
NMA	National Meteorological Agency (Ethiopia)
NOAA	National Oceanic and Atmospheric Agency
NRC	National Research Council
NWP	Numerical Weather Prediction
ORAAMP	Office of the Revision Addis Ababa Master Plan
PCC	Population Census Commission
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCM	Regional climate models

RCP4.5	Representative Concentration Pathways attain 4.5 W m^{-2}
RCP8.5	Representative Concentration Pathways attain 8.5 W m^{-2}
ROC	Runoff coefficient
SDSM	Statistical Down-Scaling Model (software)
SECR	State of Ethiopian Cities Report
SEI	Stockholm Environment Institute
SNNPR	Southern Nations and Nationalities Peoples Republic (Ethiopia)
SRES	Special Report on Emission Scenarios
TM	Thematic Map
UA	Urban Agriculture
UHI	Urban Heat Island
UHII	Urban Heat Island Intensity
UNDESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations International Children's Emergency Fund
UNISDR	UN-International Strategy for Disaster Reduction
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
WEAP	Water Evaluation and planning (software)
WG2	Working Group two
WHO	World Health Organization
WorldClim	World Climate prediction Data Portal

WWAP	World Water Association Program

CHAPTER 1

INTRODUCTION

1.1 Background

It is widely accepted that climate change has already occurred (Solomon *et al*., 2007). For example, one of the results from Intergovernmental Panel on Climate Change (IPCC) working group (WG) - I 5th Assessment Report (AR5) shows that the world average surface temperature increased by 0.85 °C during the period 1880–2012 (IPCC, 2013). A demographic change is taking place at a significant rate across the developing countries that will be expected to see an additional two billion residents in urban areas in the next 20 years, with the urban populations of Africa doubling through this period (UNDESA, 2010). This will certainly exacerbate the emissions of greenhouse gases which have been found to contribute to a rise in global average surface temperature (Brian, 2009; IPCC, 2013; Wang, 2015)

Climate related risks due to increased variations in climate and weather associated with extreme events have emerged as a key natural hazard of the 21st Century (IPCC, 2013; Hayhoe *et al*., 2013; Dastagir, 2015). Studies on both present climate variability and future climate change impacts-vulnerability and adaptation have predominantly been derived from Global Circulation model (GCM) outputs. GCMs are the most multifaceted tools currently available for simulating the global climate system (Randall *et al*., 2007).

Coupled with climate change, urbanization poses an added challenge to water resources around the world (Larson *et al*., 2013). Human induced climate change is expected to influence the quantity and quality of water resources and this requires changes in the way water resources are handled. Since urban population is expected to grows increasing the amount of existing water supply to meet the rising demand (Hanak & Lund, 2011). Studies shows cities have additional sources of water supply (like from the ground water) in order to maintain inhabited consumption levels (Alexander *et al*., 2010).

For this reason, protecting future water vulnerability is essential through interconnecting climate change and variability, water resource management including community adaptation to water scarcity (Vorosmarty *et al*., 2009). Urban growth will be affected by stressors (households, commercial, industrial and agriculture) on water demand activities due to unreliable supply to the sectors that affects business and jobs (Hurd *et al*., 1999; Larson *et al*., 2013).
World cities have seen significant changes in the strength and incidence of extreme weather events, including levels of precipitation leading to drought and flooding. Some others have changes in temperatures and lack of rainfall that has contributed to extensive heat waves and droughts. Some countries have already experienced coastal erosion and the vanishing of wetlands (Carmin, *et al*, 2012).

The IPCC Working Group II in their Report-5 (AR5) (2013) on cities has confirmed that the world's main urban agglomerations are condensed in relation to variations in observed and projected temperature. This predicted temperature change for the year 2025 verify that the vast majorities of the world's population living in the biggest urban agglomerations will be exposed to minimum 2 degree rise in temperature compared to pre-industrial period level. This means that mean temperature rise in some cities could be over 4 $^{\circ}$C (IPCC, 2013).

It is well-known that most climate change impacts will be experienced in developing countries with Africa being of utmost concern (Parry *et al*., 2007). Most of the major changes are predicted to occur in Africa on climate-vulnerable activities: since the capability to adapt may be inadequate because of technological, economic and institutional limits (Droogers, 2009).

Urbanization is occurring at a very high pace in Ethiopia. Addis Ababa is the administrative and political seat of the country and attracts the highest number of migrants from other parts of the country. This increasing population in the city leads to land use change in many dimensions and also forces the city to expand outward putting pressure on the rural land and natural recourses surrounding the city. The 2011 Development Plan of Addis Ababa City shows that the urban population in Ethiopia is growing at about 4.3 percent per annum, with the majority living in Addis Ababa (Federal Democratic Republic of Ethiopia (FDRE) Green Economy Strategy, 2011).

The Climate Resilience and Green Economy Strategic policy of Ethiopia addresses the needs of instant and efficient action to respond to climate change. These reactions include actions to lower Greenhouse gas (GHG) emissions and adaptation plan to reduce the vulnerability of the population and the economy to the impact of climate change. Also in line with the National Growth and Transformation Plan (GTP), the national access for the drinking water of baseline year 2010 is 65.8 %, 91.5 % and 68.5 % for rural, urban and combined rural and urban settings respectively. The targets to be achieved by 2015 were 98 %, 100 % and 98.5 % for rural, urban and combined rural and urban settings respectively (MoH and MoWE, *2011)*.

Despite these targets, like many other cities, Addis Ababa Cityis vulnerabile to climate change impact. Adaptation in the city has also been a major gap in climate change response, despite rapid population growth rates and serious deficiencies in water supply service provision for the householdes, commercial, industry, new developments and renewal areas of the city (Harma *et al*., 2012).

Millennium Development Goal (MDG) indicted that water must be assured for all, especially to meet the basic human needs of deprived people in areas who have been unprivileged for so long (Kreft *et al*., 2010). Additionally, water cannot be just billed to meet the increased demand from household, commercial, construction, industry and other productive sectors but must also gratify the requirements. In order to quickly assess alternative water allocation scenarios at city and reservoir level, planners and policy makers will need information on expected climate and its impact on water resources.

1.2 Problem Statement

The most significant consequences of climate change will be alterations of global scale on temperature and precipitation. The prediction of global mean surface temperature for the period 2016–2035 indicates an increase by more than 1°C above the mean period 1850–1900 (IPCC, 2013). It has also been noted that climate change impacts vary with extent from a neighborhood through national to regional scale and global stand point. Most climatic projections and studies are designed at global scale and regional scale. However, sufficient information and knowledge are needed below this scale which can be realized through correct downscaling of large scale information.

Urban scale climate information is vital since climate change is also having deep negative effects on water supply management in most urban areas (Larson, *et al*., 2013). The water supply in Addis Ababa, the urban site chosen in this study, is operated by the Addis Ababa Water and Sewerage Authority (AAWSA) which supply an average of about 80 liters per capita per day (AAWSA, 2011). According to WHO (2005), the optimal access of drinking water should be more than 100 liters per capita per day. The 65 % (195 000 m^3 / day) water is supplied from Gafersa dams, Legadadi and Dire dams. Fourteen percent of the water supplied to Addis Ababa is from the Akaki well field where as 21 % (63 000 m^3 / day) of the water is from other scattered wells and other protected springs (AAWSA, 2011). Water supply sources are under pressure due to urbanization (e.g., newly constructed housing development, offices and industries demands). Legedadi, Dire and Gefersa dam catchments are part of Awash River basin which is within the eastern Africa region affected by recent drying trend and recurrent drought (Mengistu (2016b) and references therein). Therefore climate change should be utmost concern for the water supply of Addis Ababa.

Moreover, urban growth in population and industry, converts the landscape from natural to more and more impervious urban land. The consequence of this change will have major effects on natural environment and climate. The result in land use change will cause temperatures change between the city and the outskirt of city, which is the most common change known as the Urban Heat Island (UHI).

Addis Ababa, has observed notable spatial expansion, population growth and many developmental activities such as infrastructure in roads, railway, building construction and many other activities. The resulted increase in land utilization and modification of land use and land cover change over the time has modified and will continue to modify the micro-climate of the city.

1.3 Research Aim and Objectives

The aim of the research study is to develop an improved understanding of the existing and future trends in climate and urbanization on water supply and consumption and enable the city to adapt to these compounded changes. Therefore, the research aims to achieve the following objectives:

- To assess present climate and future trends in climate over the city from gridded high resolution observational, and statistically downscaled and bias corrected GCM data;
- To investigate water supply and demand through WEAP hydrological model driven by these high resolution data sets using the different scenarios for the prediction of the relation scenario between water supply-demand and population trends, climate change and unmet demand;
- To assess spatial and temporal urban land use and land cover change and its impact on climate for the city of Addis Ababa by using land cover data from remote sensing satellite and spatial gridded climate data; and
- To develop adaptation strategies to the negative impacts of climate change and population growth on the water supply and urban heat island (UHI) in the city of Addis Ababa.

1.4 Significance of the Study

In the world increased human influence on climate, ecology, and hydrologic impact has become a critical area of research. The debate about the impact of climate change and urbanization and the impact on water supply have motivated to design and detect the present and future trends of urbanization and climate change. It is essential that the potential impacts of climate change be studied in conjunction with other trends of urban development services, given that these forces can interact in complex ways (Praskievicz & Chang, 2009).

Climate change and urban growth are global concern, assessments of impacts and adaptabilities require consideration of local contexts as a part of a wide socio-economic context on the affected and inter-dependent systems. The IPCC (2000) report explained that natural environment and human systems are affected by current climatic conditions and social and economic factors such as increasing resource demands and unsustainable management practices (Nakicenovic & Swart, 2000; Henriques, 2007).

The severity of the impacts of climate change depends upon the state of the urban environment. In particular, urban environments have their own microclimate, air quality and hydrological regimes. An increasing temperatures and/or decreasing precipitation will have a double impact: increased evapo-transpiration and lowered recharge rates reduce the total water available in the hydrological system while also increasing the total end-user demand. Supply declines while demand increases.

The global trend of urbanization and the growing population of cities require increasing volumes of water to be extracted and transported (Hunt *et al*., 2010). Securing sufficient supplies of freshwater for growing cities is therefore of primary concern, and may be seriously hindered by the spatial and temporal variability of water demand and supply (Buytaert *et al.*, 2012). Incorporating this information into the planning of water supply systems for the Addis Ababa city can ensure adequate future levels of drinking water. Therefore, this work is the first step in providing this information based on investigation of observational and model data.

This work may serve as a future reference to urbanization, climate change impact on water supply, land use change impact on urban climate and urban heat island (UHI) for the East Africa region. In addition, this investigation can be adaptable for other African cities, for the planning and management of their water resource.

1.5 Outline of the Study

This thesis is structured such that Literature reviews on urbanization and climate interactions are given in Chapter 2. Chapter 3 includes description of the study area, materials and methods used while Chapters 4 to 6 cover results and discussion on signature of present and future climate change at Addis Ababa city spatial scale (Chapter 4), impacts of climate change and population growth on surface water supply and demands of the city (Chapter 5) and impacts of urbanization and land use change on urban scale climate versus with Urban Heat Island (UHI) of the city (Chapter 6). Finally, conclusions and recommendations are given in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A review of literature on urbanization and climate change, as well as water resources in the context of global, regional, national and the city level provide the framework for this chapter. The impact of climate change on water resources and the contribution of land use change to the urban heat island (UHI) are also reviewed. Furthermore, literature on climate modeling and climate change adaptation strategies in particular on the impact on water supply and the urban heat island (UHI) effect is given in this chapter.

2.2 Urbanization

2.2.1 Urbanization in the World

In the 1950s the world population was mostly rural and more than two-thirds of people lived in rural settlements, since then world urbanization increased rapidly. In the year 2014, just over half of the world population resided within urban centers. This trend is expected to increase over the next 35 years to the extent that, by 2050, two thirds of the world's population will reside in urban areas (UNDESA, 2015).

The world urbanization prospect report of 2014 shows that in the coming decades, urbanization is expected to be global phenomena, with Asia and Africa leading in urbanization expansion compared to the rest of the world. The rate of urbanization during 2014, in Africa and Asia was 1.1 and 1.5 % per year, respectively (see Figure 2.1). However, the two regions are expected to reach the 64 % and 56 % urbanized thresholds by mid-century, respectively (Nugent and Seligman, 2008; Cincotta, 2010; Bloom and Canning, 2011; Casterline, 2011; UN-DESA, 2015).

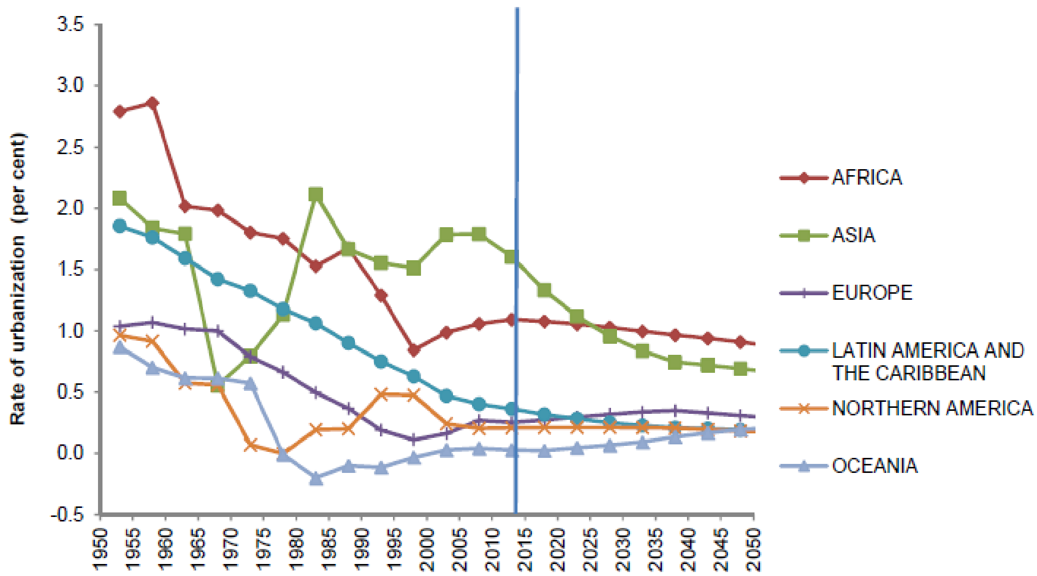


Figure 2.1: The rate of urbanization in major regions of the world between 1950 and 2050. (Source: UNDESA/Population Division World Urbanization Prospects: The 2015 Revision).

It is anticipated that by 2050 the African and Asian, population will increase by more than two thirds, which is about 90 percent increase from 1950. World urban population grew rapidly from around 700,000 in 1950 to about 3.9 billion in 2014 and is expected to reach about 6.3 billion in 2050 (UN-DESA, 2015).

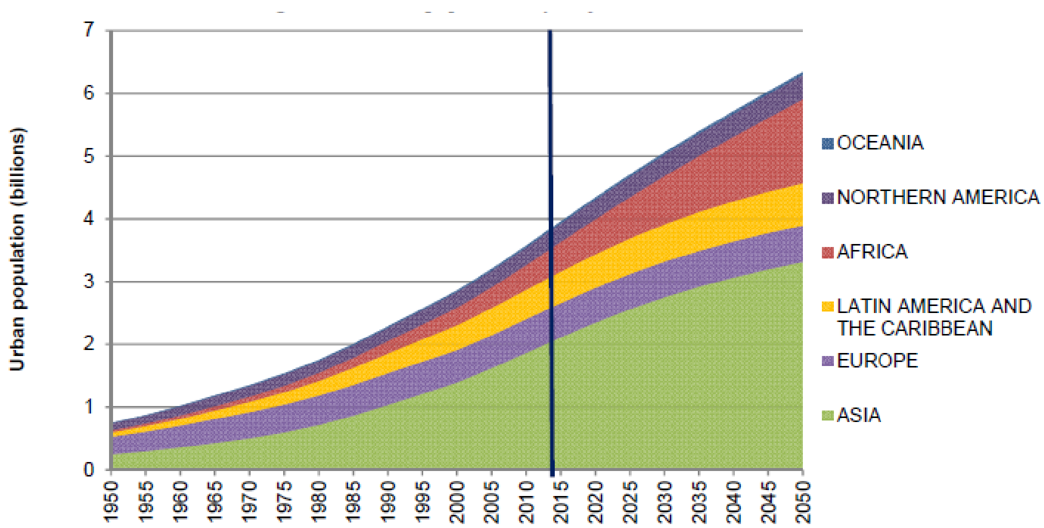


Figure2.2: Urban Population in major regions of the world (1950-2050). (Source: UN-DESA, 2015).

In 2014, half of the world's urban population lives in Asia (Figure 2.2) and the 2nd highest level of urbanization occurs within the European sub-Continent. Latin America follows by 14 % and the Caribbean by 13 % (UN-DESA, 2015). The world demographic report declared that**,** Tokyo (Japan) is the world's largest urban area with population size in excess of 37 million (Ziv and Cox, 2007; Cox & Hugh 2014)**.** The second largest population is found in Jakarta (Indonesia); Seoul (Korea) is third and the fourth is Delhi, India. Bangladesh is the most densely populated city, with population density of 45,000 persons per km^2. The population density of New York is more than 11,500 persons per km^2 and this city continues to have the largest city footprint (Cox & Hugh 2014). The 2014 Demographic of the world report indicated that there are 34 urban areas with a population over 10 million people which are considered as megacities in the world (UNDESA, 2015). Globally cites occupy about 3 % of the world's land surface area. The number of cities that exceed over 5 million had grown from four in the 1950 to fifty-nine in 2015 (Baklanov *et al*., 2006; Cox & Hugh 2014).

According to UN-World Water Report (2012), the wellbeing of urban areas is critically impacted in deprived urban slum areas. Some of the problems including the insufficient access to safe drinking water, safe sanitation and congestion of living space impact urban slum areas (Sclar, *et. al*., 2005; UN-World Water Report, 2012). These deprived areas together with the effects of climate change results in disaster vulnerabilities. In most African cities informal settlements and slums are often built in floodplains or other geographically problematic landscape areas including steep-slopes (OECD, 2016; Davis, 2004).

2.2.2 Urbanization in Ethiopia

Ethiopia has a population of approximately 87.95 million people and ranking as the third most populous country in Africa (SECR, 2015).The national population growth rate for the period 1994 to 2007 was 2.5 %; the urban and the rural rates being 3.8 and 2.3 % respectively. However as compared to Asian and other African cities, the annual urbanization growth rate in Ethiopia is slower than the other mentioned. According to population projections made by the Ethiopian Central Statistics Agency (CSA, 2013), the estimated 2012 urban population is about 17.5 million and expected to increase to close to 42.3 million at annual growth rate of 3.8 %, while the level of urbanization is expected to reach 31 % by 2037 (Golini, *et al.,* 2001; CSA, 2007; CSA, 2013).

Ethiopian urban planning regulation states that, an urban centre is defined by having a minimum population size of 2,000 inhabitants; and fifty percent of the inhabiting are engaged in non-agricultural activities (SECR, 2015). The Ethiopian Central Statistics Authority (CSA) only considers administration status to define urban centers, like regional, zonal and *Woreda* cities irrespective of population size. Some characteristics of urban settlements are concentration of population, availability of infrastructure and services and diversification of economic activities (SECR, 2015). The number of urban settlements in Ethiopia increased from 648 in 1984, to 922 in 1994 and to 973 in 2007 (Tolon, 2008**;** CSA, 2008).

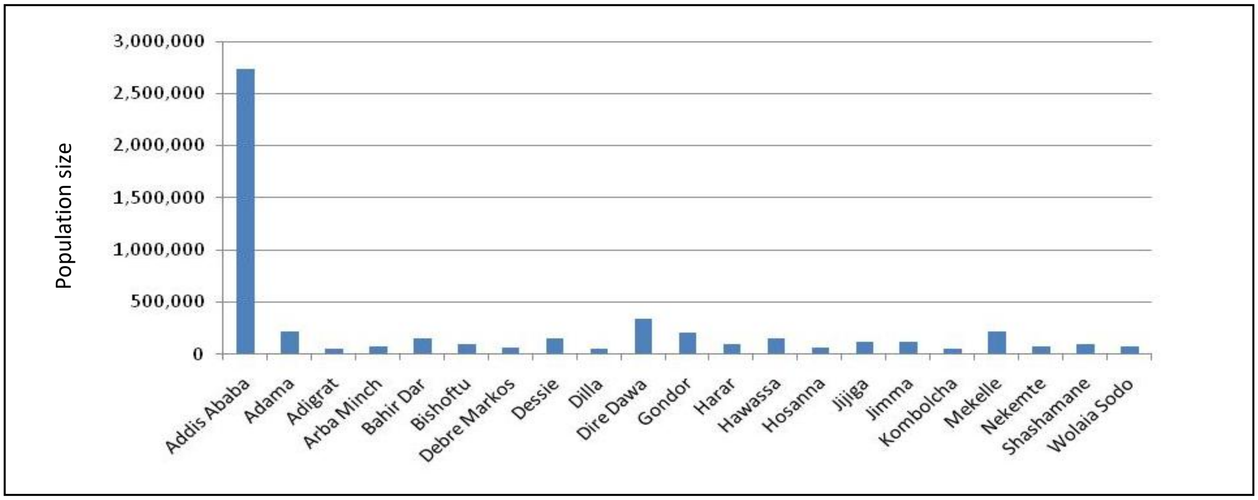


Figure 2.3: Urban population in Ethiopia (2008)**. (**Source: Central Statistical Agency (CSA), 2008).

According to a 2014 report, Addis Ababa has a key urban feature, which is the city population is more than ten times larger than the second largest urban centre, Dire Dawa city administration (Figure 2.3).

In Ethiopia there are only 16 urban centers or towns having a population of 100,000 and above (see Figure 2.4) (SECR, 2015). Together these 16 urban centers form about forty percent of the total urban population of the country. In contrast, Addis Ababa shares 11 % of the national population in 2013 (SECR, 2015).

Based on data from the Ethiopian Economics Association (EEA) (2011) and Water-Aid Ethiopia (2011), access to improved water and sanitation is increasing rapidly. In four years from 2005 to

2008, access to potable water in rural areas increased from 35 % to 52 % which shows an average rate of increase of 5.6 % per year (MoWR, 2008). An annual rate of increase of approximately 2.4 % of Ethiopia's population is gaining access to some form of improved water supply every year, and reliance on surface water is declining (Foster and Morella, 2011).

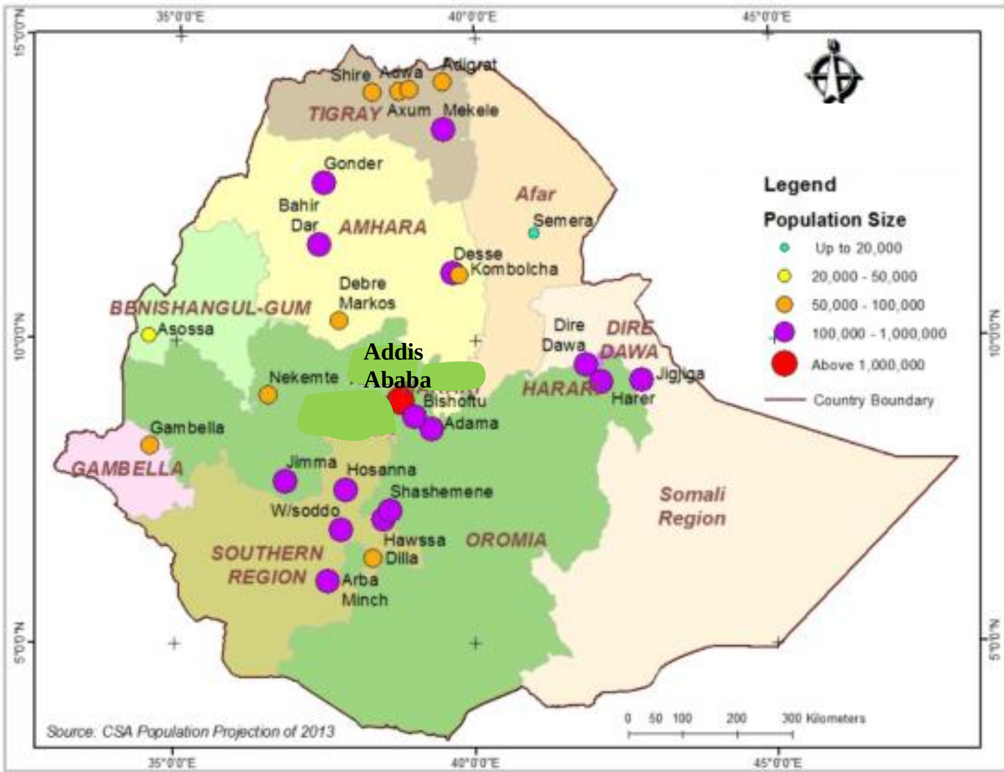


Figure 2.4: Major cities in Ethiopia (Source: State of Ethiopian City Report (SECR), 2015).

The Ethiopian Growth and Transformation Plan (GTP) sets the targets and strategies of the Ethiopian government for 2010/11-2014/15 to near-universal access to potable water in urban areas by increasing the coverage from its 68% baseline in 2010/11 to 98.5 % at the end of the planning period in 2014/15 (Ethiopian Economics Association (EEA) cited by MoFED (2012). Along with this expansion in urban water supply, the urban-rural gap in access to improved water sources have been improved but at slower rate when compared to the increase in coverage (MoFED, 2005). As indicated in Table 2.1, access to clean and safe water continues to be lower in rural areas than urban areas. Contrary to fast progress seen on access to improved water sources, progress in sanitation and hygiene are lagging behind. Only about 38% of the Ethiopian population has access to proper sanitation facilities which is very low-about two times lower than the average for low-income countries (Foster *et al*., 2011; Arsano *et al*., 2010). Official statistics indicates that Ethiopia's government capital budget expenditure for the water sector increased from 2.6 billion Birr to 3.4 billion Birr between 2007/08 and 2008/2015, suggesting a 31 % growth rate in nominal terms (MoFED, 2012).

Table 2.1: Improved sources of drinking water in Ethiopia over two decades: 1990-2010.(Source: WHO, 2010).

Year	Urban [%]	Rural [%]	Country [%] **
1990	77	8	19
1995	82	12	23
2000	88	18	29
2005	95	24	35
2008	98	26	38
2010**	96	31	41

Note: ** Country level coverage was calculated based on the reported urban and rural figures and by multiplying these by the respective proportion in total population of Ethiopia (84% rural and 16% urban).

2.2.3 Urbanization in the city of Addis Ababa

The Office of the Revision Addis Ababa Master Plan (ORAAMP, 2002) study shows that, historic physical expansion of the built-up area of the city of Addis Ababa was divided in to five development periods (1887-1936, 1937 -1975, 1976 – 1985, 1986 – 1995, and 1996 - 2000). The first period is the early development period that took place from 1887 to 1936 and is known for its haphazard and extended settlements of military camps and the landlords' occupation of large compounds as villages. The extended area was between Gulale and Yeka along West to East transect and Entoto and Bekulo-Bet along North to South transect. In this period (1937-1975), the total built up area was equal to 1863.13 hectares. Assuming constant growth in each year the average growth of the built up area was 37.26 hectares per annum during this period (Leulsegged *et al.*, 2012). In the period between 1976 and 1985, the built-up area increased by 4788 hectares, thus increasing the cumulative total to 10,838 hectares. The physical expansion of the city between 1986 and 1995, were 2925.3 hectares, increasing the cumulative total to 13,763.3 hectares (Fig. 2.5).

Simultaneously, expansion took place in all peripheral areas of the city, where both legal and squatter settlements were established (Leulsegged *et al.,* 2012).Out of the total 94,135 housing units built in the city between 1986 and 1995, 15.7% (14,794 housing units) were built by squatters (Melesse, 2005). During the physical expansion between the year 1996 and 2000, the built-up area of Addis Ababa increased by 909.4 hectares, reaching a cumulative total of 14,672.7 hectares (Melesse, 2005).

Currently, the total area of the city is 526 km^2 including squatter settlements areas. Within this area of the city, the population in Addis Ababa is about 2,980,000 according to 2011 census which was conducted by the Central Statistical Agency of Ethiopia (CSA, 2012). In 2013 the total population of Addis Ababa was estimated to be 3,120,000 (AABoFED, 2013). It is also projected that over the next 23 years and by 2039 the population will grow at medium rate of 2.5%, reaching about 5-6 million people (Addis Ababa City Government, 2012).

Table 2.2: Addis Ababa Population growth from 2009-2013. (Source: CSA, Population Projection for Ethiopia, Addis Ababa Bureau of Finance and Economic Development (AABoFED, 2013)).

Region	Year	Total Population
	2009	2,851,000
	2010	2,913,000
Addis Ababa	2011	2,980,000
	2012	3,048,631
	2013	3,120,000

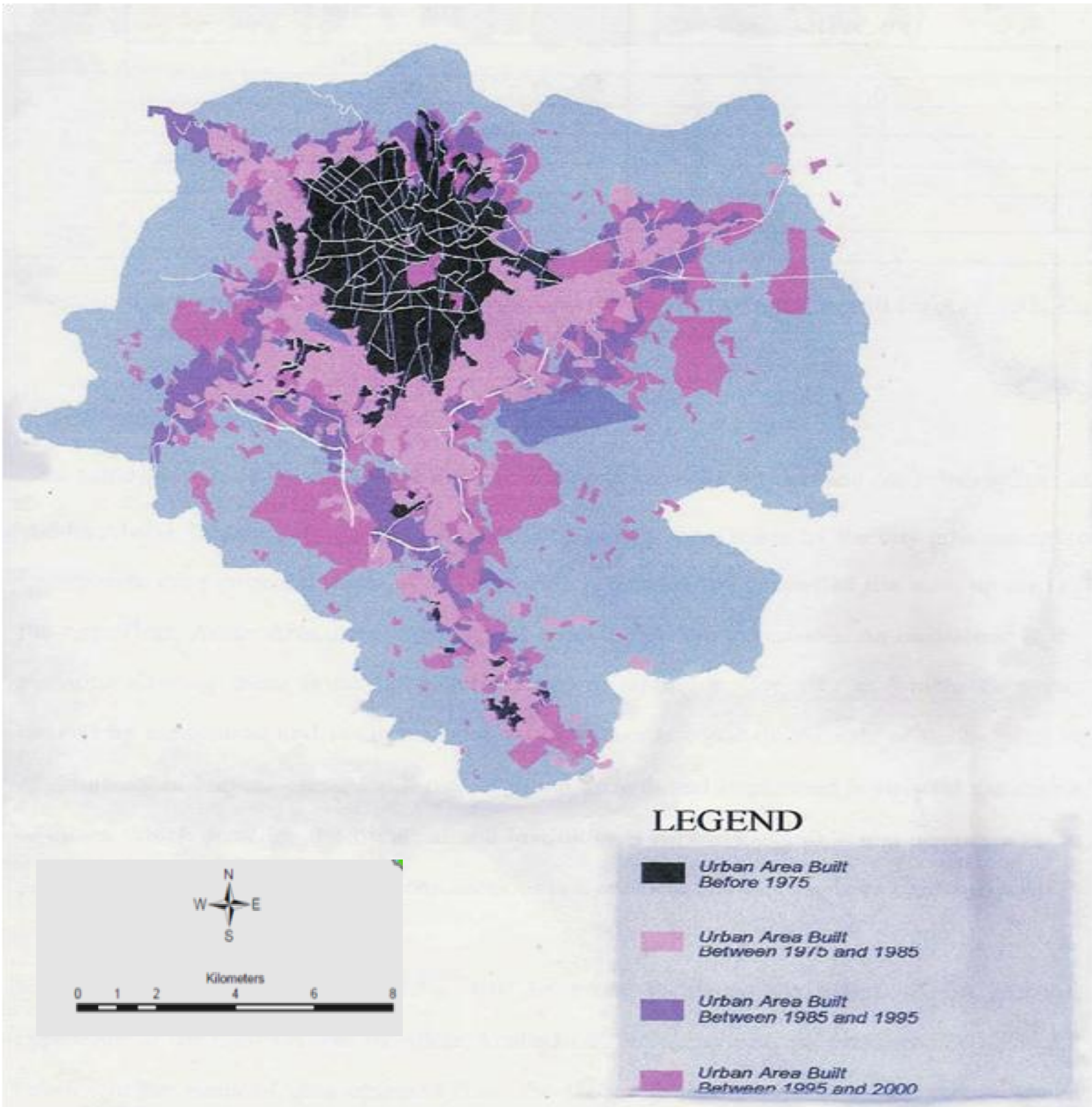


Figure 2.5: Physical Expansion trend of Addis Ababa. (Source: Office of the Revision Addis Ababa Master Plan (ORAAMP), 2002).

2.2.4 Land use of study area

The 2014 land use and land cover character of the city of Addis Ababa is an important aspect for understanding the proportion of urban features and activities. Fig. 2.6 shows the map, with scale of 1:150,000, of urban land-use cover for the study area, representative and available meteorological stations according to Addis Ababa and surrounding Oromia region integrated plan (AACPPO, 2014). The dominant land use features are residential with mixed-use (which accounts for an area of 153.1km^2), green and other open space (which accounts for an area of 279.9 km^2), road net-work and transport terminal (which accounts for an area of 57.6 km^2), Rivers (which accounts for an area of 10.9 km^2), Manufacturing and Storages (which accounts for an area of 17.2 km^2). Figure 2.7 shows that vegetation covers are observed at the mountain in the north and along river buffer areas. The central parts of the city mainly Arada, Addis Ketema, Lideta and Kirkos Sub-cities have less vegetation cover. Manufacturing and storages dominate the southern part of the city, which is around Akaki kaliti sub-city area; whereas mixed-use is found in the central part of the city, the open and farmland occurs around Bole Airport area. The elevation of the city at Bole International Airport is 2408 meters, while the elevation at Entoto Mountain, Northern part of the city, is more than 2444 meters above sea level. The radius of the city has expanded, particularly to the east and south.

2.2.5 Vegetation Cover of Addis Ababa

In the city of Addis Ababa recreational parks are formal green spaces, usually used for public ceremonial services such as weddings (MoUDHC, 2014). At present there are 18 recreational parks in Addis Ababa. Some of them like Gion-Central Park and Addis Zoo parks are administered by the Mayor’s office. In the city, Africa Park is administered by private investor. The remaining recreational parks like Bihere-Tsige Park are administered by the respective sub-city Beautification, Parks, and Cemetery Development and Administration Offices.

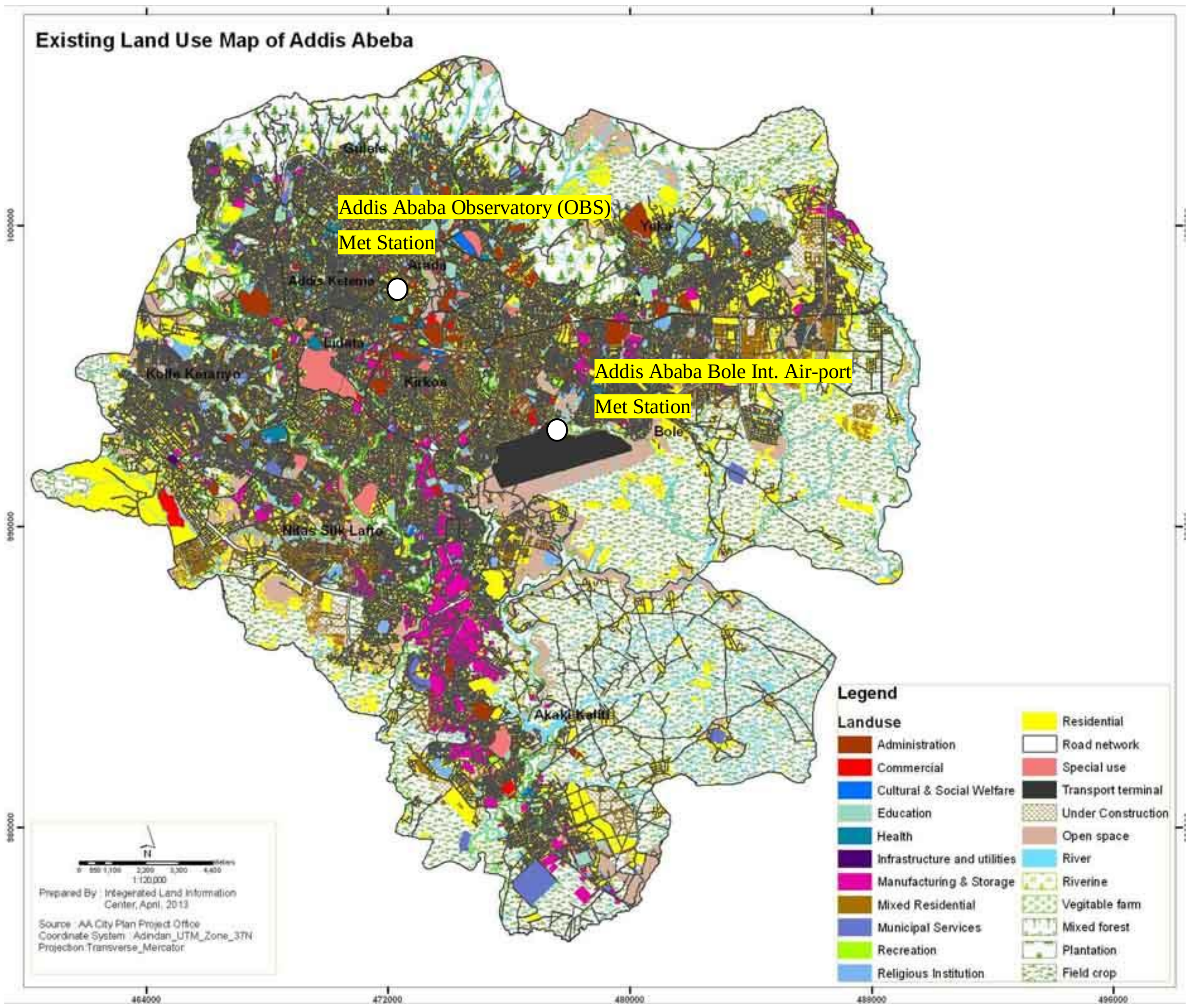


Figure 2.6: Existing (2013) Land Use Map of Addis Ababa and Two Meteorological station Locations. (Source: Addis Ababa City Planning Project Office (AACPPO), 2014).

However, the green space and park distribution areas of Addis Ababa is much lower than some African cities leading to smaller green space cover per person (Fig. 2.7). Addis Ababa has only 0.94 square meters of green space per capita in 2010 (MoUDHC, 2014). The World Health Organization (WHO) suggests a minimum of 9 m^2 square meters of green space per capita (World Health Organization, 2010); this amount is only suitable if the greenery is reachable and accessible.

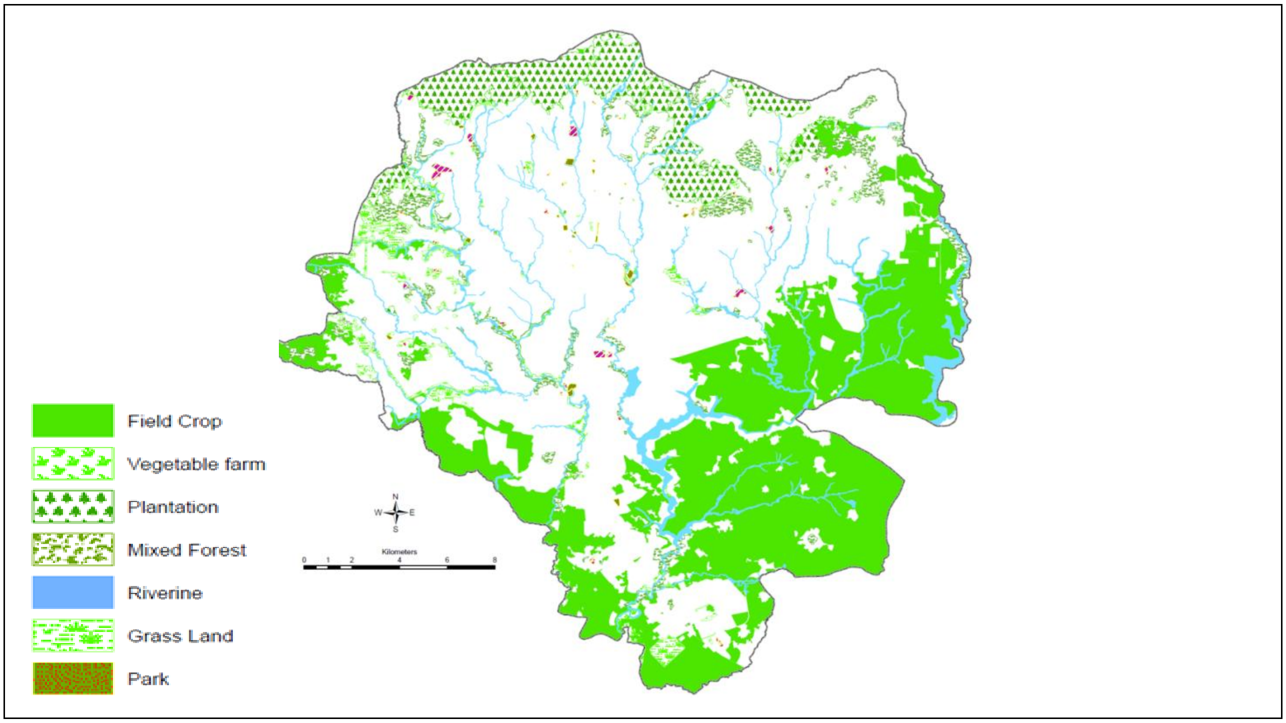


Figure 2.7: Green infrastructure of Addis Ababa**.** (Source: Addis Ababa Master Plan Project Office (AACPPO), 2014).

Table 2.3: Proposed total number of parks and classification in Addis Ababa. (Source Addis Ababa Master Plan Project Office (AACPPO), 2014).

Park Classification	**Park area**	**Population catchment area**	**Approximate distance from home**	**Area (ha)**	**Total number of parks**
City Park	>10 ha	100,000-500,000	10 km	2,435	18
Sub-city Park	1-10 ha	50,000-80,000	5 km	240	76
Woreda Park	0.3-1 ha	10,000-15,000	1.5 km	55	106
Neighborhood park	< 0.3 ha	3,000-5,000	300 m	90	-

The current rapid developments of the city center of Addis Ababa have left lower proportion of parks and other green spaces than prescribed by WHO (Fig. 2.8). The new Master Plan of Addis

Ababa made in 2016 was proposed to increase the green cover of the city to reach 7 m^2 of Green area per person as shown in Table 2.3 (AACPPO, 2014). However, most of these proposed parks have not yet been implemented. In some sub-city, it has been well fenced but the park is currently used by small and micro enterprises producing cement products.

2.2.6 Economy of Addis Ababa

Addis Ababa is an autonomous city with the city council having ten Sub-Cities (CLUVA, 2010). The socioeconomic activities of the city is mainly from trade and commerce, manufacturing and industry, construction, transport and communications, hotel and catering services, education and health services. The service sector contributes about 74.96 %, industry 24.67 % and urban agriculture 0.35 % to the GDP of the city in 2009 (Addis Ababa City Government, 2012).

According to the UN- Habitat (2008) the life expectancy of males in Addis Ababa is sixty-three and females are about sixty-seven years. Addis Ababa is the base and seat of the Economic Commission for Africa and the African Union (AU). Addis Ababa was established in 1886, since-then the city serves as capital city of Ethiopia (UN- Habitat, 2008).

Gebre and Rooijen, (2009) stated that compared to other cities in the country, sanitation services are better in Addis Ababa. In 2009, 75 % of the city used pit latrines and only about 10 % of the residential and commercial components of the city activity connected with sewerage system. Most of the pit latrines discharged into the rivers and storm water drainage network (Elala, 2011; AABoFED, 2016).

2.2.7 Water Supply in Addis Ababa

Water is the basic need, both quantity and quality of supply directly affects the wellbeing of the society in the city. Water accessibility and adequacy is one of the circumstances that make urban areas to be comfortable place to live. However, this demands substantial efforts. For example in 2012 alone, ground water source (accounting for 70,152,807 m^3) and surface water source (accounting for 42,062,760 m^3) were added to the supply system in order to meet the demand of the increasing city residents. The amount of water production per day also shows a considerable improvement from 232,000 m^3 in 2008 to 374,000 m^3 in 2012. Water coverage in the city of Addis Ababa, had increased from 52 % in 2008 to73 % in the 2011 and made substantial performance improvement in the year 2012 when the coverage reached 94 % (AABoFED, 2016).

However, poor maintenance supply systems and lack of new technology combined with fast population growth and climate change are causing water shortages in many areas of Addis Ababa. High volumes of wastage due to defective piping also cause shortage of water (UN-Habitat, 2008).

2.3 Climate Change Overview

Climate change is defined as a mean of alteration of the climate of the world that humans are causing, through clearing forests, fossil fuel burning and other practices that increase the greenhouse gases (GHGs) concentrations in the atmosphere (UN-ISDR, 2009).

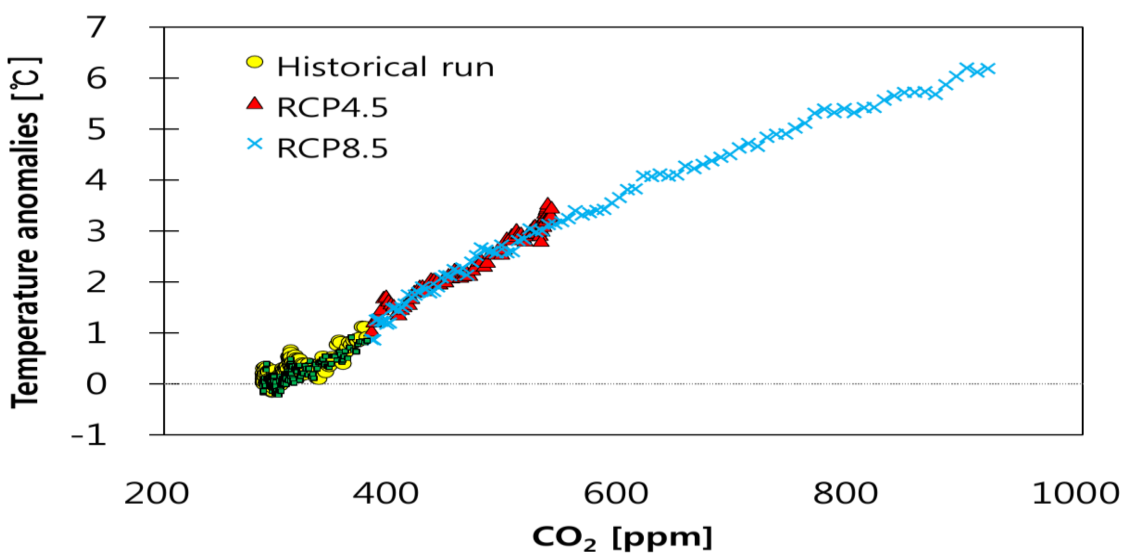


Figure 2.8: Global Temperature Anomalies with CO_2 emission. (Source: Parry *et al*., 2007).

This is similar to the official definition by the United Nations Framework Convention on Climate Change (UNFCCC) that climate change is the change that can be attributed *"Directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods"* (Parry *et al*., 2007; UNISDR, 2009).

Climate change is caused by the global increase in atmospheric concentrations of greenhouse gasses (GHGs). These gasses include methane (CH_4) (mainly from landfill), carbon dioxide

(CO_2) (mainly from combustion of fossil fuels) and (NO_x) oxides of nitrous (mainly from vehicles, industrial energy resource and agriculture) (UNISDR, 2009; Brain, 2009). It is now broadly accepted that climate change is a current occurrence and further change and variability are inevitable.

History shows that scientists have known that the atmosphere's greenhouse gases act as a "blanket" which catches incoming solar energy and keeps the Earth's surface warmer and the increase of this atmospheric greenhouse gases would lead to additional warming (Fig. 2.8) (Parry *et al.*, 2007). The concentration of greenhouse gases in the atmosphere is higher than it has been for the past 500,000 years, rising of CO_2 to 70% between 1970 and 2004 alone (UNISDR, 2009).

For the most part, a climate change is denoted by change in temperature and precipitation (Coquard *et al*., 2004; WMO, 2012; Htut, *et al.*, 2014). Climate change also exhibits itself in the form of extreme events such as drought and heat waves including shortage in rainfall, and conversely more severe or increase in rainfall causing floods (IPCC, 2013). These changes have the potential for dire consequences for the health and well-being of communities and the local economy. Climate change may also reduce water quantities in rivers and lakes due to increased evaporation and less-inflow (Knutti and Tomassini, 2008; Rochdane *et al.*, 2012). Lower water levels may have serious impacts on much needed water supply, recreation activities, aquatic animals, hydroelectric generation and water quality.

Climate change can damage natural environments including ecological and botanical extinctions. Anthropogenic forced climate change could make any attempt to protect remaining species even more difficult (IPCC, 2007). Transportation sector is also highly vulnerable to climate change, the efficiency and durability of road and rail infrastructure may be reduced by extreme weather events (Nemry & Demirel, 2012). Shortage of rainfall and high temperatures could impact ground water sources through lowering of water table levels (IPCC, 2013). Rising temperatures and extreme weather events will all have direct effects on urban residents. In most developing countries climate change could reduce potable water supply and hydroelectricity production as water levels decrease at a time of increased demand (Hurd, *et al*., 1999). Increased insurance losses due to more extreme weather events and loss of productivity for health reasons would further burden the local economy (Htut, *et al*., 2014).

2.3.1 Observed Climate Change in the World

Over the last century, between 1906 and 2005, the average global temperature rose by about 0.74 ^{o}C. This has occurred in the following two phases, from 1910s to 1940s and a more strongly forced change occurred from the 1970s to the present (Parry *et al.*, 2007). The IPCC WG-I 5th Assessment Report (2014) shows that the global average surface temperature has raised by 0.85°C for the period between 1880–2012 (Taylor *et al.*, 2012; IPCC, 2013).

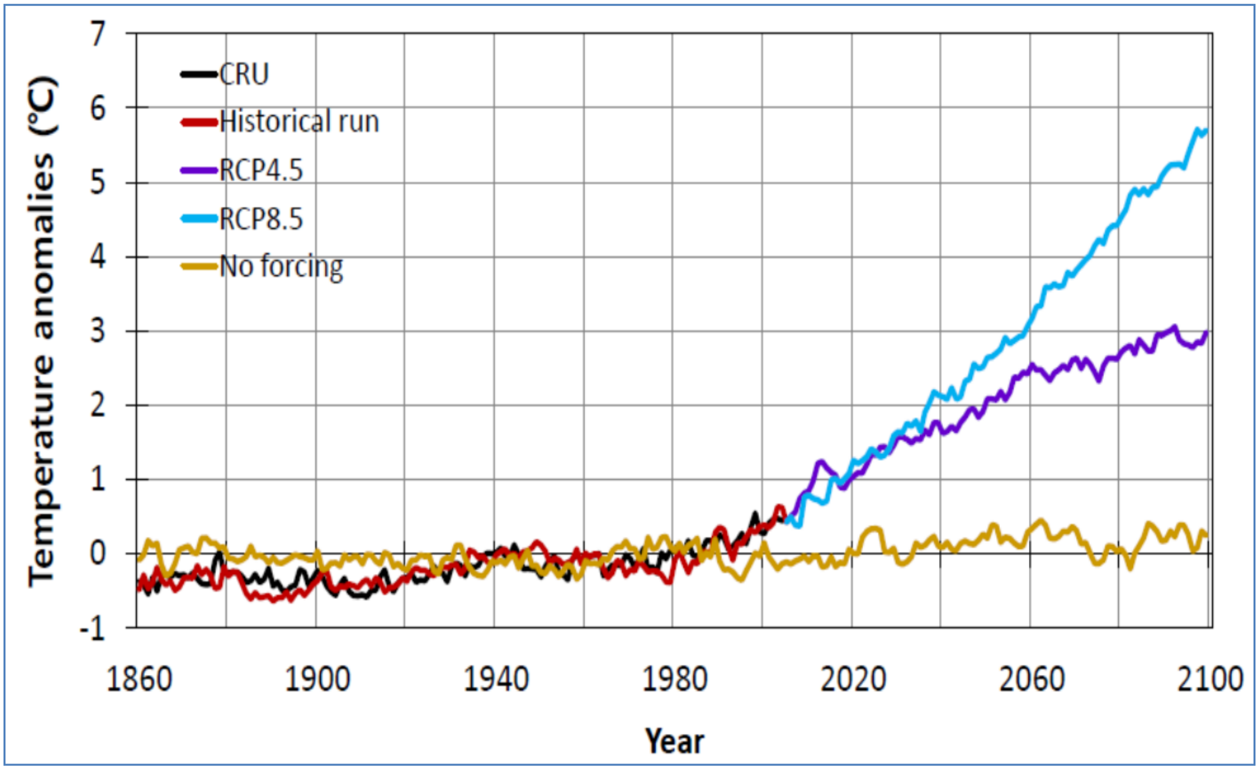


Figure 2.9: World Average Temperature Anomalies (Source: IPCC, 2013).

In the past few decades a warming trend is observed and this is projected to continue in the present year 2017 and beyond. The World Meteorological Organization (WMO) has ranked 2016 as the warmest year on record since mid-1800s (Tsidu, 2016a; Mengistu Tsidu, 2016b and references therein). Human induced global warming is evident and increasing.

In the past severe flash floods occurred in many countries, particularly in Africa, Balkans, South Asia, and Central and South America (WMO, 2014). The climate variability create these kinds of extreme events every year, and the increased occurrences of floods globally are as a result of increased energy within the hydrological cycle due to higher levels and constant increase of greenhouse gases in the atmosphere (Jones and Hulme, 1996). Consequently improved understanding on scientific modeling techniques, increased progress on quality of observed weather data enable more accurate understanding and potential adaptation into extreme climate events (Hansen *et al*., 2010).

2.3.1.1 Temperature

The 2014 global average surface temperature was comparable to the 165 years on record. The global average temperature anomaly for the year 2014 was 0.57 °C which is above the 1961–1990 average temperature (See Fig 2.9). The three other warmest years are 1998 (0.52 °C), 2005 (0.54 °C) and 2010 (0.55 °C) (WMO, 2015).

2.3.1.2 El Niño/Southern Oscillation (ENSO) and La Niña

The El Niño Southern Oscillation (ENSO) is a naturally occurring phenomenon which involves fluctuating ocean temperatures in the eastern equatorial and central Pacific, coupled with atmospheric changes (Trenberth, 2013; WMO, 2015). El Niño occurs when large scale warming of water surfaces take place in the central and eastern equatorial Pacific Ocean. La Niña are connected with large scale cooling of the ocean surface temperatures in the same region of the eastern equatorial central Pacific oceans. El Niño and La Niña had major influence on climate patterns in different parts of the world. Scientific modeling of ENSO is able to make reliable projections within a range of up to nine months into the future; thus assisting in preparation for the ENSO associated hazards such as floods, heavy rains and drought. El Niño has the overall effect on increasing global average surface temperatures, while La Niña will have the contrasting cooling. Fig. 2.10 shows that 1997/1998 was the strong El Niño event followed by two La Niña events that occurred from mid-1998 to early 2001, with a clear impact on global temperatures (Fekadu, 2015; WMO, 2015).

2.3.1.3 Precipitation

According to NOAA, world average precipitation in 2014 was near to the long term average of 1,033 mm. Areas of notably low precipitation included particularly the eastern Brazil, south west United States, north-east China, which all experienced drought in 2014. In the same year areas of high annual precipitation included southern Brazil, northern Argentina, Bolivia, and the Balkans

(WMO, 2015). Southern Ethiopia and Central Africa also experienced low precipitation (Fig. 2.11).

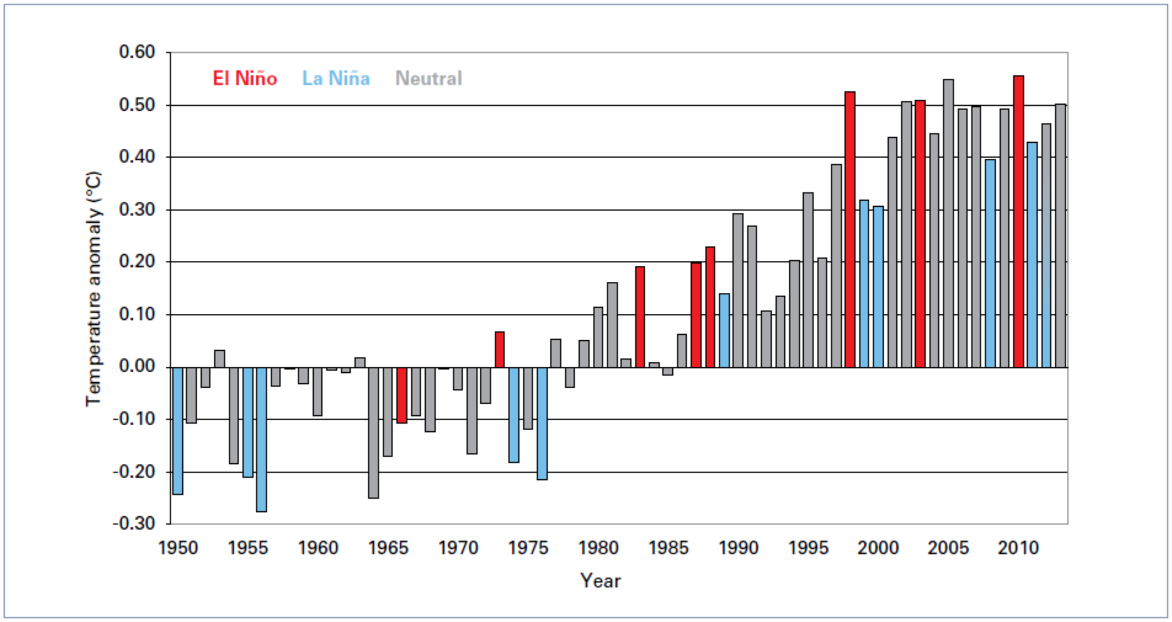


Figure 2.10: Annual global temperature anomalies (compared to 1961–1990 mean) for the period 1950–2013; La Niña years which are strong shown in blue; moderate or strong El Niño years are shown in red; normal years shown in grey (Source: WMO, 2015).

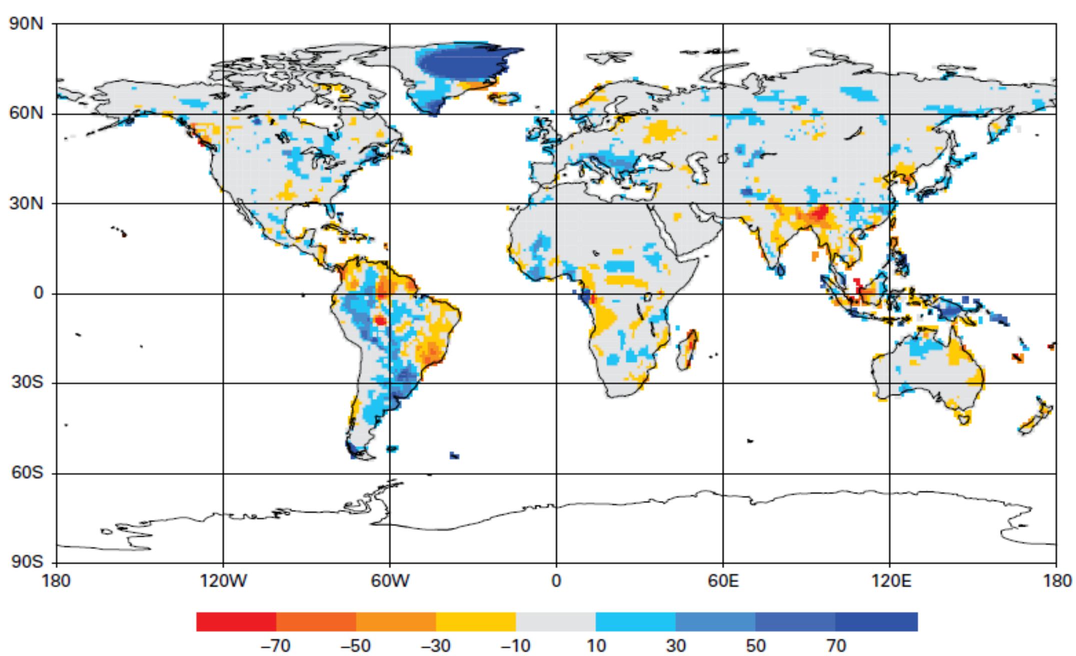


Figure 2.11: World Precipitation totals for the year 2014 as anomalies relative to the 1951–2000 average (Source: WMO, 2015).

2.3.2 African Climate

The IPCC WGII AR5 **(**2014) report, indicates that over the past 50 to 100 years mean annual temperature analysis indicates a trend in increasing temperature across the African content. The most recent review (2014) of climate in Africa based on the annual temperature anomalies assessment indicates that 2014 was the second warmest year on record since 1950 (see Fig. 2.12). Over African content, 2010 was the warmest year on record. The temperature trend since 1950 over Africa shows an increase of 2 °C per century. From 1990 to 2014 the rate reached 3 °C per century (Fig. 2.12 broken trend line).

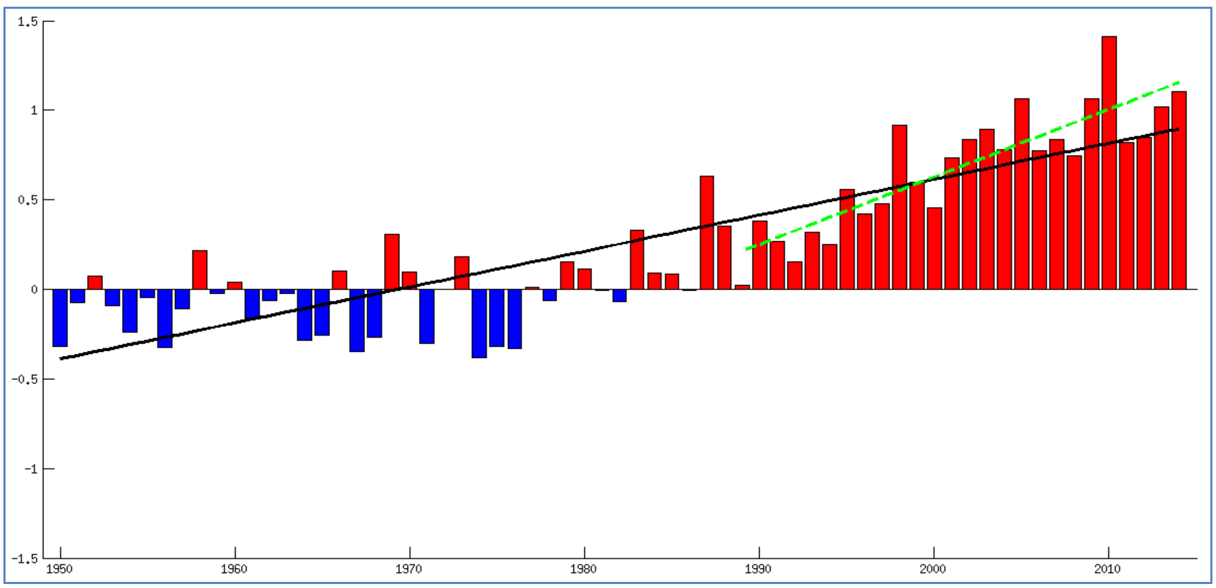


Figure 2.12: Temperature anomalies (°C) for Africa for 1950-2014 relative to 1961-1990; gridded data based on station observations. (Source: ACMAD-MESA, 2015; from NOAA/NCEP/CPC/ CAMS)

According to World Meteorological Organization (WMO) annual statement, the global precipitation in 2014 was near to the long-term 1951–2000 average of 1,033 mm around the world. On this particular year of average precipitation, above the annual mean of 1981-2010 precipitation was recorded over northern Mali, southern Algeria, southern half Morocco, southern part of Sudan and adjacent areas in Ethiopia and Eritrea, parts of Botswana and Namibia (Fig. 2.13). In 2014, drought with moderate severity occurred over Somalia, southern Mauritania and northern Senegal (ACMAD-MESA, 2015).

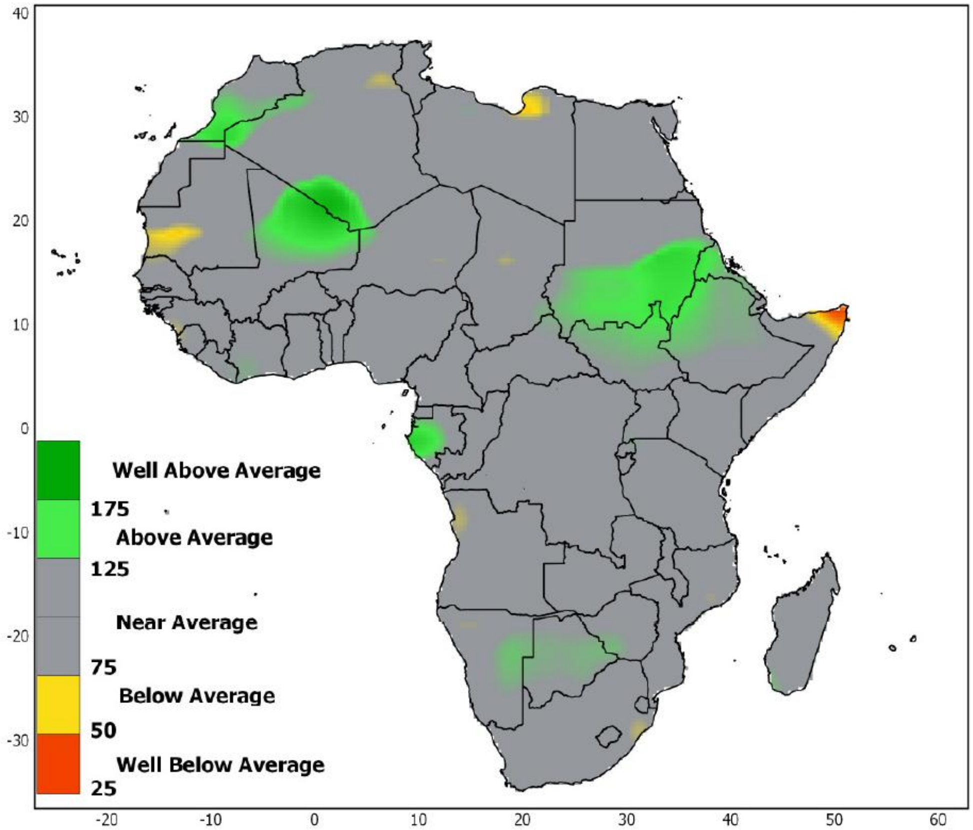


Figure 2.13: Average annual precipitation change from the mean (1981–2010) over Africa for the year 2014; this gridded precipitation data estimates from satellite and gauge station data analysis with respect to 1981-2010. (Source: ACMAD-MESA, 2015; from NOAA/NCEP/CPC/CAMS-OPI, 2015).

2.3.3 Climate trends and extremes over Ethiopia

Ethiopia is a country located in the Horn of Africa lying between 3-15 degrees north latitude 33-48 degrees east longitude**.** Ethiopia covers a total land surface area of about 1.113 million km^2 (CSA, 2000) and bordered on the west by Sudan, the east by Somalia and Djibouti, in the south by Kenya, and the northeast by Eritrea. The landscape of Ethiopia in Fig. 2.14 has 4 main regions from east -west there is rift valley, southwestern highland, southern highlands and different Plateaus (typical flat-topped mountains). The Ethiopian Plateaus comprises more than half of the country (Abbate *et al*., 2015). In northern Ethiopian Plateaus, there are numerous high mountains such as Ras Dashen which is 4,543 m AMSL (Berhanu, et al., 2015). The deep rift valley cut the plateau slopes from southwest to northeast.

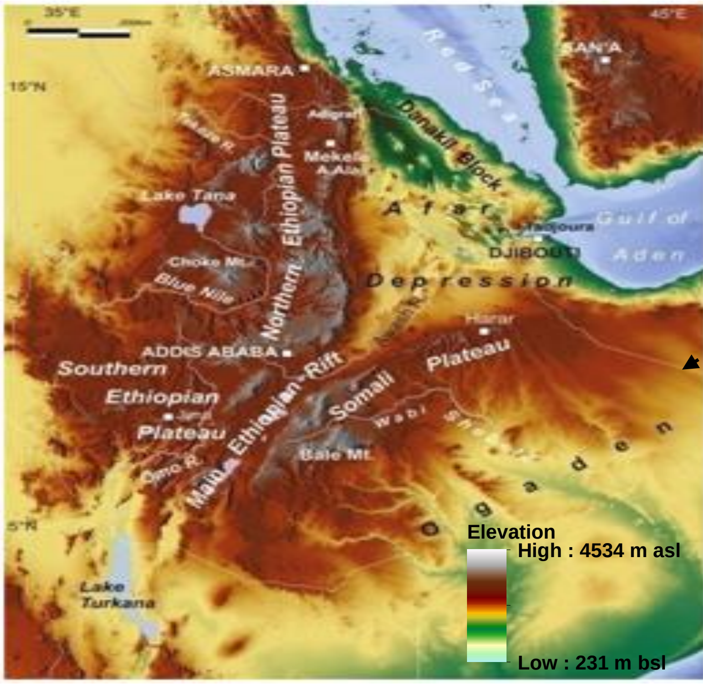
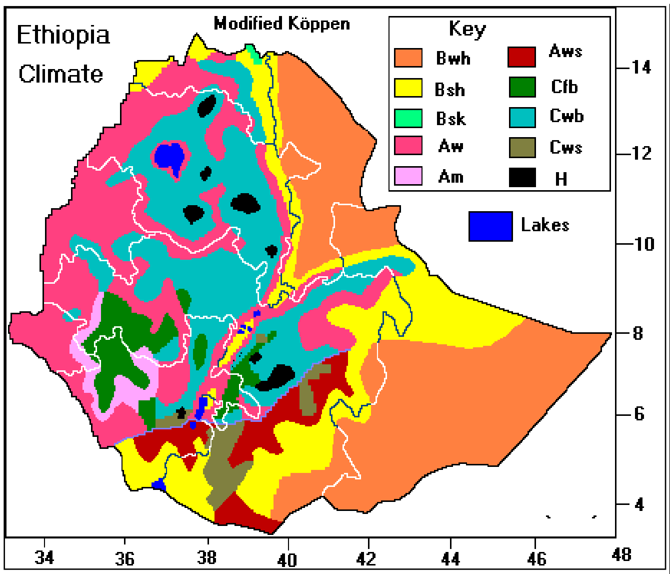


Figure 2.14: Elevation map with major topographic elements in Ethiopia. (Source: Abbate, *et al*., 2015).

Table 2. 4: Traditional climate zones and physical characteristics; Source Gonfa (1996).

Zone	Altitude (meter)	Rainfall (mm/year)	Average annual temperature (°C)
Wurch (upper highlands)	>3,200	900-2,200	< 11.5
Dega (highlands)	2,300-3,200	900-1,200	17.5-11.5
Weynadega (midlands)	1,500-2,300	800-1,200	20.0-17.5
Kola (lowlands)	500-1,500	200-800	27.5-20.0
Bereha (desert)	Under 500	Under 200	> 27.5

The weather system in Ethiopia is variable, and factors that affecting the systems are latitude, altitude, wind, and humidity (Degefu, 1987; Tsidu, 2012). Ethiopia has a diversified climate ranging from hot and semi-desert to mild and humid topographic elements. Gonfa (1996) classified Ethiopian climate into five major climate zones based on Koppen's and Thornthwaite's classification schemes of the rainfall regimes, and agro-climatic zone (Fig. 2.15). The highland part of the country including Addis Ababa has a *weynadega* or temperate climate. The southwestern highlands have *tropical rainy* and *warm temperature* climate, southern highlands have *tropical rainy* climates, while the eastern lowland of the country have *hot arid* climate. High rainfall variability on both temporal and spatial scales are typical characteristic for climate in Ethiopia (Gissila et al., 2004).There are three meteorological seasons in Ethiopia; these are based on means of rainfall and temperature of the country. These seasons are locally known as Bega, Belg and Kiremt (Degefu, 1987; Gissila *et al.*, 2004; Korecha, and Barnston, 2007; Tsidu, 2012).



Legend Key description	
Bwh-	Hot Arid Climate
Bsh-	Hot Semi-Arid Climate
Bsk-	Cool Dry Climate
Aw-	Tropical Climate (with distinct dry winter)
Am-	Tropical Rainy Monsoon Rainy Climate (with short dry season)
Aws-	Tropical climate (criteria of both winter and summer are met)
Cwb-	Warm Temperate Rainy Climate (with dry winter)
Cfb-	Warm Temperate Rainy Climate (with distinct dry season)
Cws-	Warm Temperate Climate (criteria of both winter and summer are met)
H-	Cool Highland Climate

Figure 2.15: Climatic zones of Ethiopia (Source: Gonfa ,1996).

Seasonal climates are influenced by the Indian Ocean current, Central African or Congo Air-mass, South Atlantic Ocean and the Asian cold land-mass. The seasonal rainfall in Ethiopia is controlled by the seasonal migration of the Inter-tropical Convergence Zone (ITCZ), which follows the position of the sun relative to the earth and the associated atmospheric circulation (Degefu, 1987; Fekadu, 2015).

Annual mean minimum temperature difference from the mean (1971-2000) has increased at a rate of 0.37 °C per decade over the period 1951 to 2006, although the trend has varied substantially over shorter periods (Fig. 2.16). The recent 20-year was characterized by increased rate of warming compared to the first and central segments (1951-1986) of the records (Brohan *et al.*, 2006).

a)

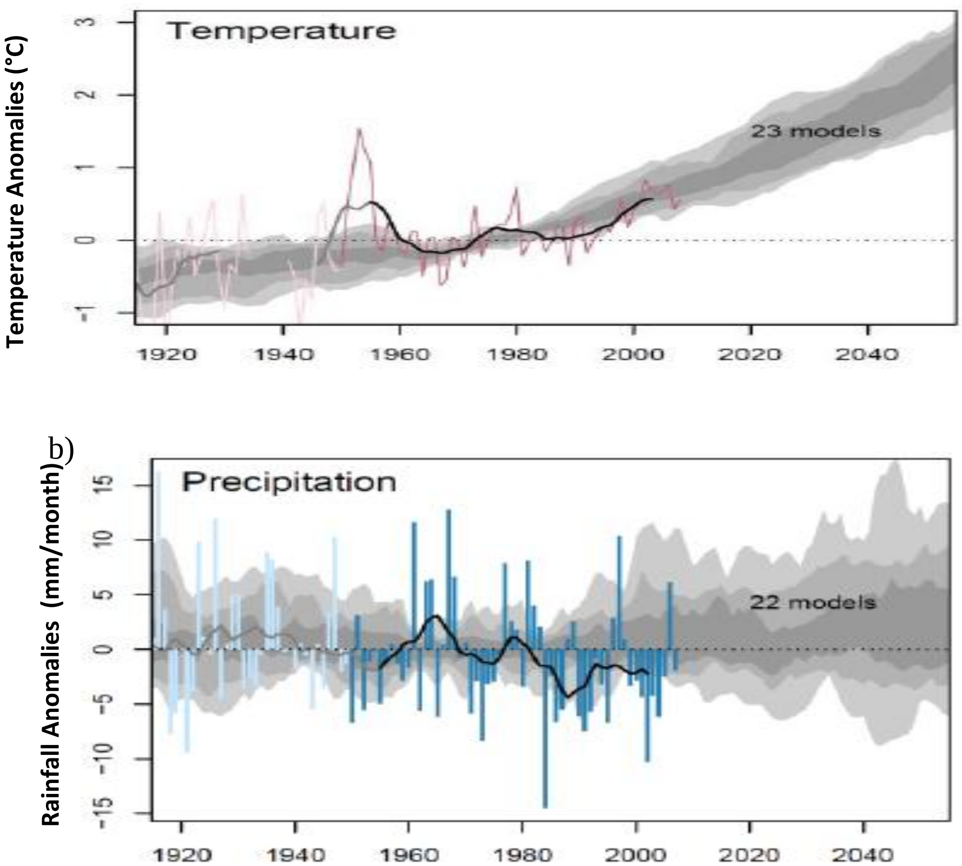


Figure 2.16a) Observed variation of mean annual minimum temperature 22 models and b) precipitation with projected changes by twenty-two global climate model over Ethiopia. (Source: Brohan *et al*., 2006; Keller, 2009; Parry *et al*., 2007).

Temperatures are very much modified by the varied altitude of the country. In general, the country experiences mild temperatures for its tropical latitude because of topography (Gonfa, 1996). Spatial mean annual temperature and precipitation for the period 1950-2000 are presented in Fig.2.17 a-c. Mean annual minimum temperature over the highlands of the country reaches to -1.1 °C and the mean annual maximum temperature over the lowlands of Ethiopia will reach about 37 °C (See Fig. 2.17 a-b). Both rainfall and temperature varies greatly with altitude. Observed mean annual rainfall distribution exhibits a substantial spatial variation that ranges from 2163 mm over south western parts of the country to less than 99 mm over the Afar and Ogaden lowland as shown in Fig. 2.17c.

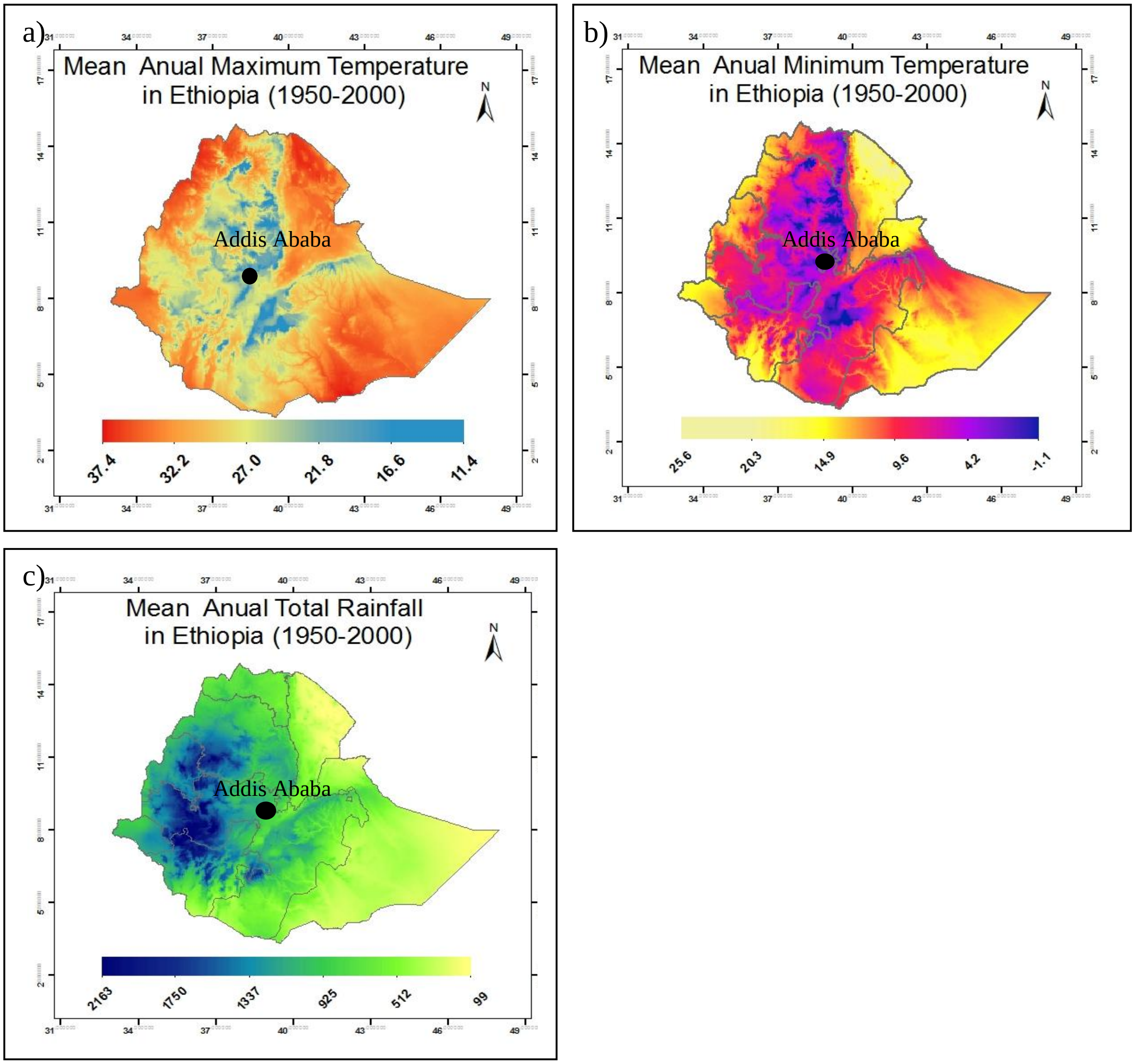


Figure 2.17: a) Mean annual maximum, b) Minimum temperature and c) Mean annual total precipitation over Ethiopia; derived from WorldClim reference climatology for 1950-2000.

Drought is negative rainfall anomaly or below the long term mean, which is normally defined as some percentage reduction from the long term average annual or seasonal rainfall (Keyantash & Dracup, 2002; Wilhite, 2000). Fig. 2.18 shows that rainfall in Ethiopia showed a high variability over time. Consequently, meteorological drought years with respect to the (1971-2000) were

1959, 1965, 1984 and 2002, while 1958, 1961, 1964, 1967, 1968, 1977, 1993, 1996, 1998 and 2006 were wet years (See Fig. 2.18).

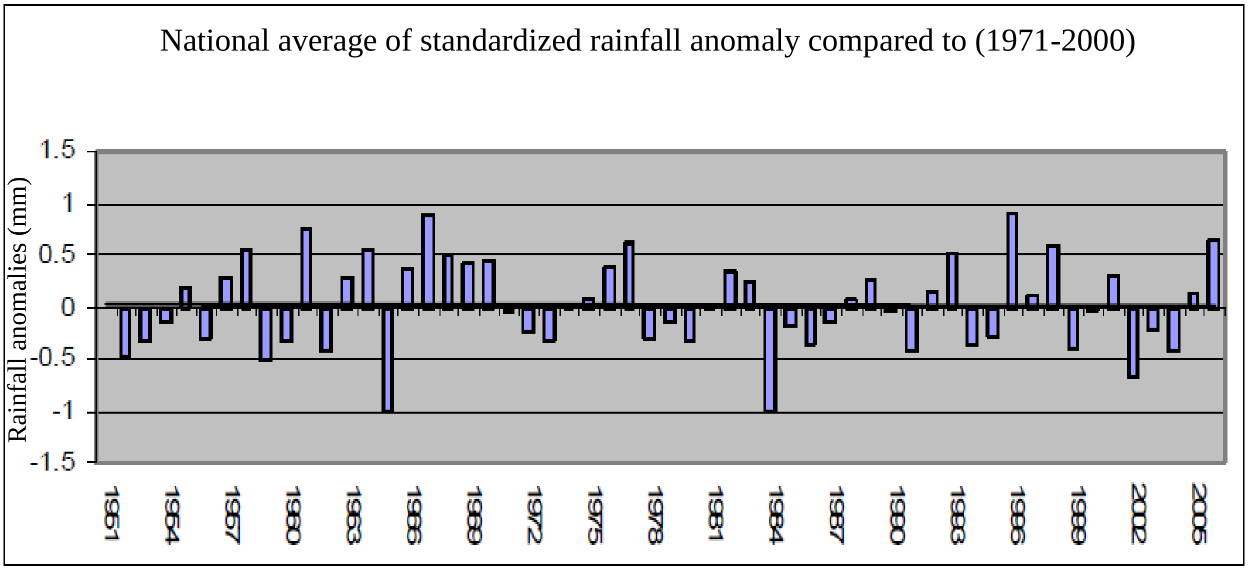


Figure 2. 18: Mean Annual Rainfall Anomalies (Source: NMA, 2007).

Analysis of high rainfall during MAM over Ethiopia (Fig. 2.19a-c), for example, shows that there is a statistically significant linear trend with northwestern Indian Ocean SST warming trend impacting the rainfall trend during March, April and May (MAM) over Eastern Africa in general (Mengistu, 2016b).

Fig. 2.19 b) for wind and MSLP anomalies both over the continent and Indian Ocean shows shift of the low-level wind confluence zone southward in the response to warm SST anomalies over the Indian Ocean (Mengistu, 2016b). The oceanic forcing response by the atmosphere will led to the increase of MSLP over much of Africa except southern Africa regions and decrease over the Indian Ocean and western Asia (Fig. 2.19 c) (Mengistu, 2016b).

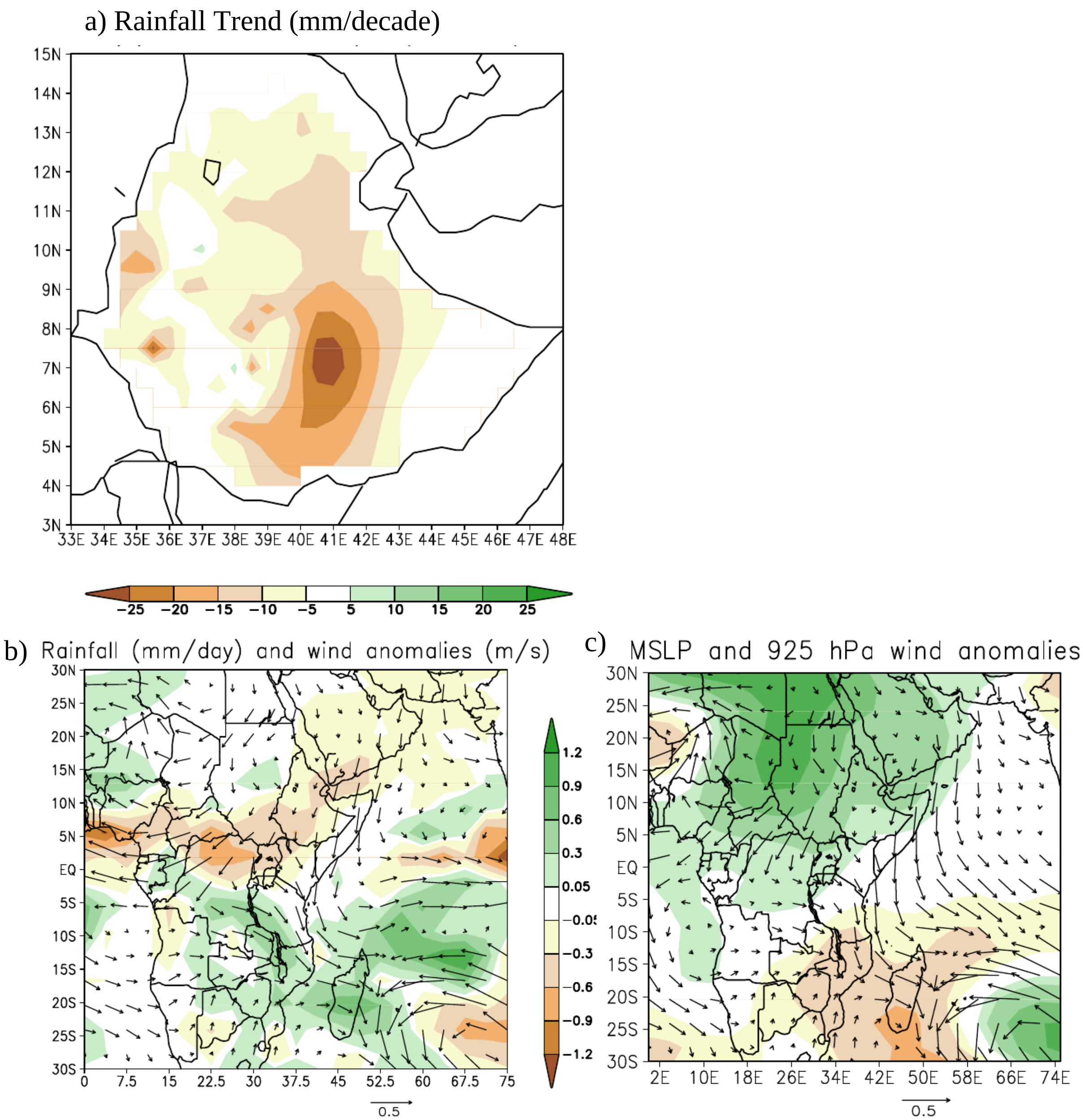


Figure 2.19: a) Rainfall Trend (mm/decade) in Ethiopia, b) Eastern Africa rainfall and wind anomalies and c) Mean Sea Level Pressure and wind anomalies.(Source: Tisdu , 2016b).

2.4 Urban Scale Present and Future Climate

In the past few hundred years the concentrations of human population increased in urban areas resulting in settlements now exceeding the population of rural areas (Martilli, 2007; UN, 2012; Grimmond *et al*, 2014; Grimmond *et al*. 2015). Most of the cities in the world are situated in developing countries (UN, 2012). Cities are fundamentally dependent on basic services and infrastructures such as water and energy supply, storm water management systems, transport as well as communication systems (Martilli, 2007). Urban areas are sensitive to climatic conditions and their variability, and have thoughtful impacts, direct and indirect, on services within cities (e.g. water supply, transportation, construction, energy demand, etc.) and beyond (particularly if the city is regional and national economic importance) (Zhu, 2009). Cities are also crucial points for driving economic and societal progress, at local and regional level (Olaide *et al*., 2013). Thus cities will provide enormous potential for adaptation and mitigation to changing atmospheric conditions, and benefits will grow from enhanced prediction through models, data and climate services (Olaide *et al.*, 2013).Urban areas range from megacities to smaller urban areas; these settlements have an important common feature: impervious built surfaces, dense populations, emissions of pollutants, waste, heat, etc (National Research Council, 2010; Pinet, 2014).

Cities with complex infrastructure and with expansive sizes may be increasingly vulnerable to climate change. Most urban areas are major drivers of economic growth, but they also result in unbalanced growth with poor urban population. Therefore, the need to study the effect of population growth and urbanization on local climate and their effect on global warming is important. Urban areas often share similar characteristics; making them more sensitive and vulnerable to climate and weather variations such as impacts on water resources affecting socio-economic activities (NCR, 2012; UN, 2014; Baklanov *et al.*, 2017). Atmospheric flow influenced by cities features like impervious materials and vegetation cover will affect heat absorption of the surface, water permeability of the surface regime and deposition of pollutant deposition (Rosenzweig *et al*, 2006). The release of anthropogenic heat leads to urban heat islands (UHIs) which are urban areas of warmer temperatures compared to nearby rural areas (Chan *et al*., 2008; Baklanov *et al*., 2017). These temperature differences are of such magnitude that they interrupt regional air circulation. Wind circulation can be disrupted due to high rise buildings. The atmospheric disturbances can lead to distorted levels of precipitation and air pollution (Zhang, 2011; Baklanov *et al*., 2017).

Cities are affected by two main mechanisms. First, the urban features such as heat radiations and morphology continually influence local temperatures, precipitation and air circulation. Second, changing of atmospheric pollution from chemical emissions will change climate and weather, both at city and suburbs areas (Baklanov *et al.*, 2006). The impervious urban land covers increase as the result of growth in population and urban sprawl expansion. This change in land cover have significant effects on local climate and weather (Oke, 1982; Xian & Crane, 2006).

Currently cities around the world are substantially affected by climate change. Climate change impacts water resources, food security, environmental health, and infrastructure, (amongst other). Cities thus need to be ready to adapt to climate change (Baklanov *et al*., 2006).

The Urban Heat Island effect (UHI) in a city develop when large areas of natural vegetation (land cover) is replaced by built surfaces that retain or store incoming solar radiation during the day and then re-radiate it at night (Oke, 2004). This slows the cooling process thereby keeping night-time air temperatures high relative to temperatures in less urbanized areas. Arnfield (2003) conducted in-depth assessment of the impact of urbanization on the climate of the cities. In London (UK) a study by Howard on Urban Heat Island (UHI), indentified that urban centers can be up to several degrees warmer than the adjoining countryside (LCCP, 2006).

In contrast with vegetated surfaces, more solar radiation is retained by building materials through the day (LCCP, 2002). In the urban layer there are many factors to increase the Urban Heat Island Intensity such as air conditioning, transportation, energy use for cooking and industrial activities (Wilby, 2008; Block *et al*., 2012). Fig.2.20 illustrates the non-urban energy balance contrast to the urban energy balance. Vegetation plays an important role through evapo-transpiration and surface cooling (Rosenzweig *et al*., 2006).

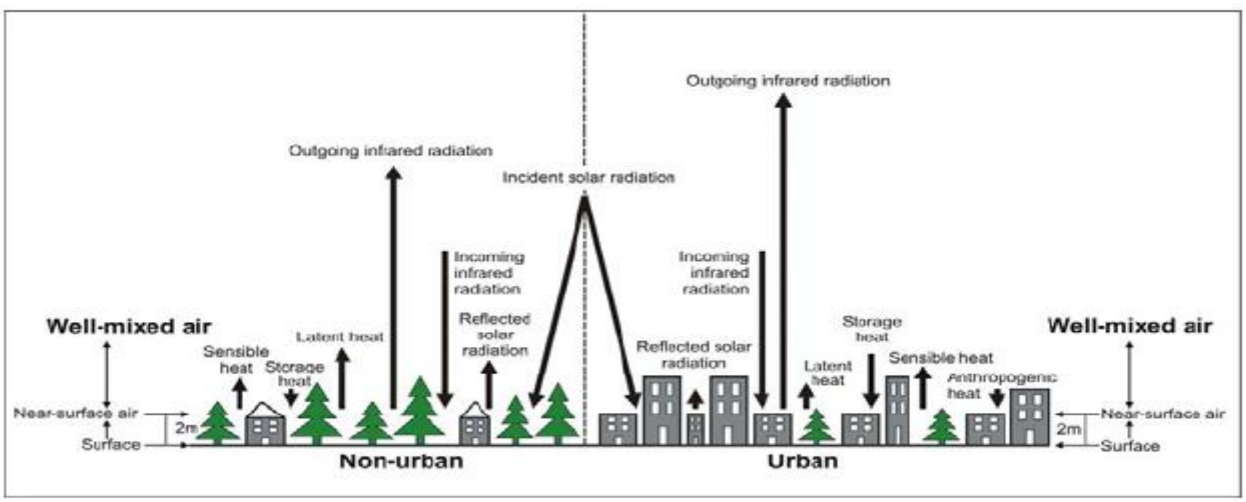


Figure 2.20: Urban to non-urban energy balance**. (**Source: Rosenzweig *et al*., 2006).

Some studies have addressed the management of weather and related risks, and the impact of future climate change. In some cities (e.g., Lisbon and Shanghai) the UHI is being mitigated in urban centers by cooling roofs, urban green space management, and introducing more water features. These methods of reducing the UHI are also done in New York, Brazil, and Tokyo (Nakicenovic & Swart, 2000; Wilby, 2008).

The study by Wilby (2007) revealed that in the late 1950s the night time heat island temperature rose by about 0.1 degree Celsius per decade. The study for London City indicates that by 2050, the nighttime UHI could rise by 0.5 °C in August and autumn months (Wilby, 2007). In the City of Tokyo a study by the IPCC shows an UHI derived rise of 0.5 ºC by the 2050s. Studies in New Jersey City revealed an increase in heat waves worsen the existing UHI (Rosenzweig *et al.*, 2006). UHI have substantial impact on heat related stresses due to increasing night time temperature (IPCC, 2013).

It is important to estimate the Urban Heat Island Intensity (UHII) in urban planning reduction strategies. In the past decades research have shown the emergence of urban heat island phenomenon in many developing countries in Ethiopia by Kifle (2003); in Indonesia by Sarkar (2004); in Mexico by Garcia-Cueto *et al*., (2007); in Nigeria by Akinbode *et al*., (2008); in Sri Lanka by Manawadu and Nirosha (2008); in Chile by Pena, (2008); in Turkey by Toy S., 2010; in Oman by Charabi and Bakhit (2011); in Argentina by Camilloni and Barrucand (2012) and others).

Several recent studies have also considered what is needed to enhance predictive capabilities of UHI (Fisher *et al*., 2005; Martilli, 2007; Wilby, 2008; Zhu *et al.*, 2012; Olaide, *et al.*, 2013; Pinet 2014; Grimmond *et al*., 2015). For instance, Wilby (2008) used SDSM to predict future UHI for the city of London. With greater demand for modeled climate information in large and megacities, it is anticipated that the world regional climate centers would extend its efforts to address climate information for urban communities. Urban scale climate information is essential for urban decision support systems. These information systems need to focus on spatial and temporal extents such as from a very short time range to a decadal scale as this will minimize disasters by informing city officials to prepare planning for adaptation and mitigation initiative scenarios.

Tree planting is used for mitigation and reducing of the UHI in cities such as New York (USA) and Camden (UK) (Rosenzweig *et al*., 2006; Kleerekoper and Salcedo, 2012). Research show that the presence of vegetation in urban areas reduce energy demands for air conditioning, as well as reduce health risks through removal of urban air pollutant (Oke, 1982; Cleugh & Grimmond, 2012; Wilby, 2007).

2.4.1 Addis Ababa Climate

The mean annual maximum temperature of Addis Ababa is 24 °C, and the mean annual minimum temperature of the city is 12 °C. The mean monthly rainfall is high in July and August which is 260 mm. The mean annual rainfall in the city of Addis Ababa is about 1255 mm (Kifle, 2006). Addis Ababa has bi-modal precipitation distributions, with much of its annual precipitation occurring during Kiremt (June to September) and Belg (mid-February to mid-May) (Fig. 2.21). There is significant intra-annual variability in precipitation (Kifle, 2006).

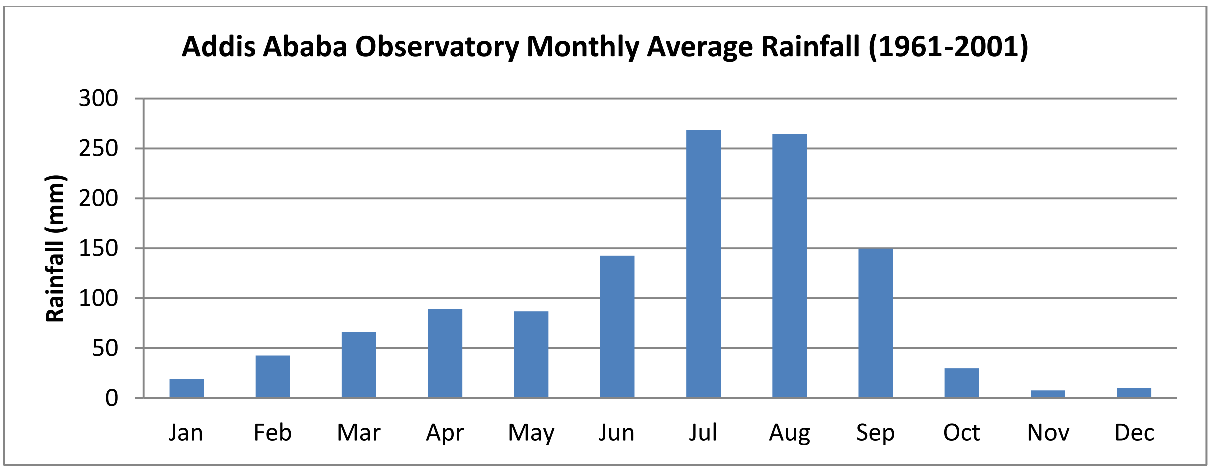


Figure 2. 21: Addis Ababa OBS weather station average monthly Rainfall (mm) (1961-2001).

By looking at a long history of observations, variability in rainfall and changes in temperatures over time are identifiable. The maximum and minimum temperature anomaly, shows, notable warm periods in the city of Addis Ababa, that have occurred in the 1997 and early 2003 (Fig. 2.22 a-c). For precipitation, below the mean annual total rainfall (1255 mm/year) (1971–2000) was observed for the years 1965, 1975 and 1994. The year 1965 was the driest year on record which was 400 mm below the mean annual total rainfall (Fig.2.22a). Periods of above average annual precipitation are also clearly evident in the historical records, such as the 1977 and 1995. Since 1991 the average annual maximum temperature anomalies have increased by about 0.5 to 1 °C above the mean of (Fig. 2.22b). However, annual precipitation does not seem to have a visible trend.

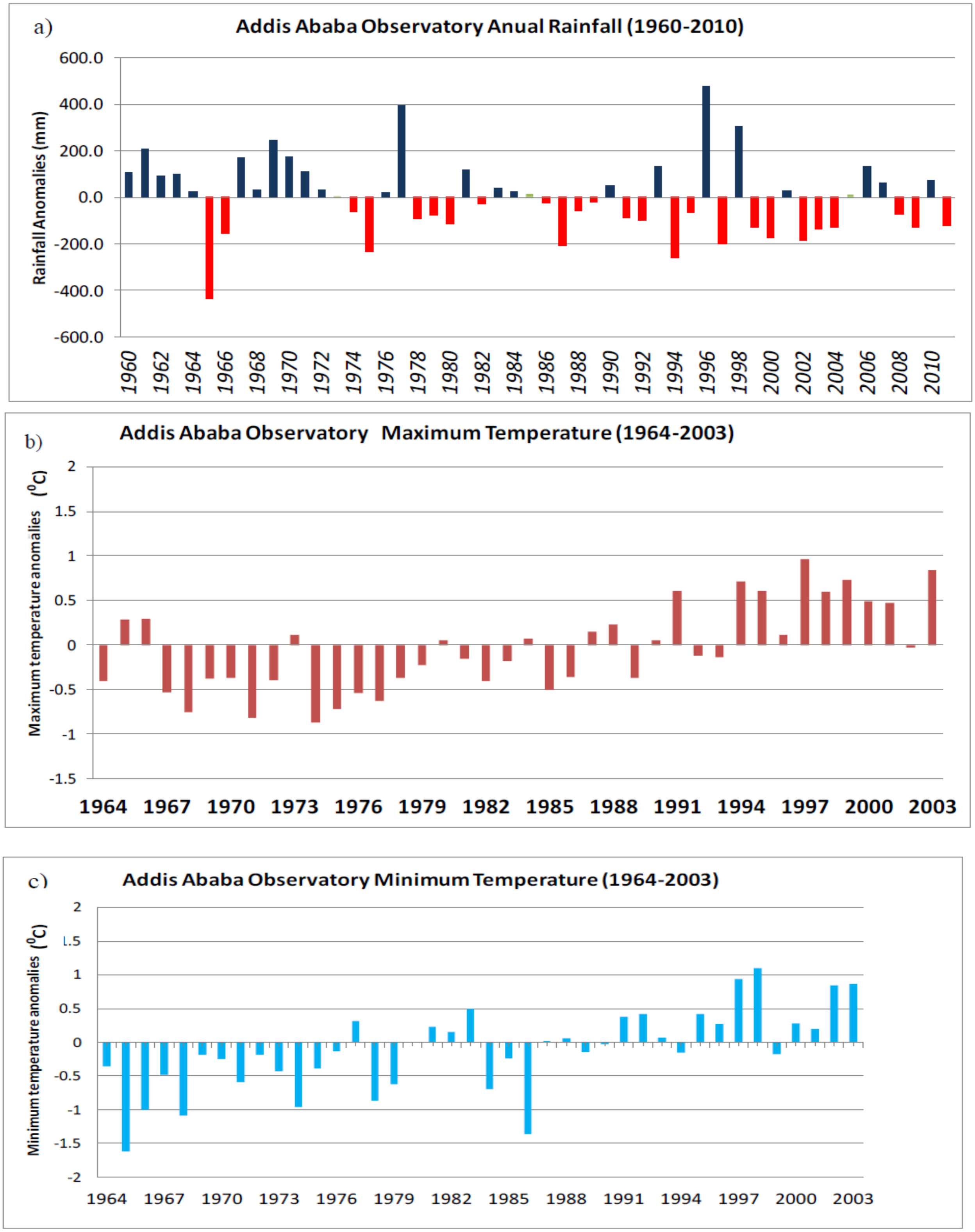


Figure 2.22: a) Annual rainfall, b) Minimum and c) Maximum temperature anomalies relative to the 1971-2000 for Addis Ababa Observatory (OBS) Station.

Addis Ababa city has contributed to climate change as the population has more than tripled from 500,000 in 1960 to about 3,000,000 in 2012. This urbanization-induced rapid population growth will largely drive the extent and rate of environmental change. Many of these changes are related to the climate and atmospheric composition over cities, including canopy cover, thermal sensation and various forms of air pollution. Human settlements modify the materials, the structure and the energy balance of the surface and the composition of the atmosphere compared to the surrounding 'natural' terrains.

2.4.2 Water supply and climate change

Globally highlands of densely populated areas, such as for example highland of sub-Saharan Africa (including the Ethiopian plateau, Great Lakes area and the Rift Valley), are distinguished by a very high population pressure on fragile ecosystems (Aguilar-Manjarrez, *et al*., 2010; Turral, *et al.,* 2011). Increase and expansion into marginal land lead to increased risk of landslides, increase rates of erosion and changes in patterns of runoff, result in land degradation and decrease in productivity (Turral, *et al.,* 2011).

Water sustains food chains and is one of the most significant resources even more so than oil (Morrison, *et al*., 2009). Rapid urbanization presents global challenges to increasing access to potable water (WHO/UNICF, 2012). Globally, the number of urban inhabitant who has access to potable water for the period 1990 to 2008 was about 1.052 billion, while the global urban population increased by 1.089 billion. The increase of informal settlements and their deprived sanitation environments obstruct the efforts to increase access to potable water in urban areas (Morrison, *et al*., 2009; WHO/UNICF, 2012). On top of population growth, the practices of rapid urbanization pose challenges to increasing access to potable water.

Climate change is expected to increase water stress, resulting in drinking or potable water supplies facing increased demand from contending uses of water for domestic and non-domestic use such as commercial and industries (Rosa and Clasen, 2010). An increased occurrence of climate related natural disasters and extreme weather events might result in an increased loss of water related infrastructure. The world assessment of resilience water supply systems against prediction of climate changes shows that by 2020s and 2030s, the sustainability of the current progress towards the Millennium Development Goals (MDGs) may be considerably undermined (Howard et al., 2010).

Climate change will plausibly increase demand of municipal drinking water and that used for agriculture due to extended dry periods and severe drought. Commercial impacts of water shortage may include increase in the price for water regulatory limits for water use or water rationing conflicts between people groups and other water users and rising demand for water efficient technologies and products (Solomon et al., 2007; Bates *et al*., 2008).The sustainability of water resources is adversely impacted by increasing demands (Roy *et al*., 2010). The WHO and UNICEF (2010) reported that, about 87 % of the global population obtains drinking water from improved sources and the corresponding figure for developing regions are more than 84 %. Worldwide water use abstraction for agriculture is the highest (70 %), industrial use is around 20 %, and domestic water use is about 10 % (WWAP, 2009; Buytaert *et al*., 2012). Ground water abstraction due to increasing water demands causes problematic ecosystem functions and reduction in water tables (UNEP/GRID; Arendal, 2008). A study by Foster *et al*., (2007) also shows that, cities in China that have excessively used ground water caused reduction in water tables and decrease in quality (Stephen, *et al.*, 1998).

A study in California indicated that extensive amount of reservoir storage from rivers and streams will provide enough capacity to hold a change in inflows for most years. Nevertheless, some reduction of inflow volumes due to reduction in precipitation on watersheds might reduce the water supplies. Most prediction studies show that the results of lessen inflow to the reservoir due to reduced precipitation appear more important than the shift of season specifically for water supply area (Rochdane *et al*., 2012**).**

Drought in sub-Saharan Africa is one of the dominant climate risks. Floods are destructive to infrastructure, transportation, goods and service flows and could contaminate water supplies and cause waterborne diseases to become epidemics (IPCC, 2014b). Due to high population growth water supply pressure is increasing in Africa. Even though water resources are plentiful in some regions, water shortage has been a major restriction to the economic development of certain regions (Parry *et al.*, 2007). The minimum amount of water required for economic and social development (including for human health) is estimated at list 135 liters per person per day (UN-WATER, 2012). When development increases water use also increase to support the economic growth. In Africa, sub Saharan countries are among the most threatened by water stress. This is as a result of extreme variability, seasonality of water resources, and decreasing stream-flows (forecast in coming decades) (Rochdane *et al*., 2012**)**.

A study in Northern China indicated persistent water scarcity. In 2008 for example, infrastructure construction for water cost about $2 billion for a 191mile water-way, also the city of Beijing has received additional water from the less populous southern regions in China. Studies estimated that Beijing's water reservoirs have been depleted to one tenth of their capacity, and two thirds of Beijing's water supplies are currently drawn from underground sources. São Paulo, Brazil had a shortage in hydro-electric energy production as a result of drought in 2001. The effects of the drought based energy rationing on the national economy, was a reduction of 2 percent of the country's GDP, which equals to approximately US$20 billion (PACINST, 2006).

2.5 History of Climate modeling

2.5.1 General Circulation Models (GCMs)

During early 20th century Vilhelm Bjerknes first showed how to compute dynamics of weather at large scale using the equation of motion and state (McGuffie and Henderson-Sellers, 2005; Weart, 2007). Some of the equations are; conservation of mass, Newton's laws of motion, thermodynamic energy equation and the hydrodynamic state equation. Vilhelm Bjerknes's mathematical model explained how momentum, mass, moisture and energy are conserved in interactions amongst air parcel (Weart, 2010). During World War I, based on Bjerknes' equations Richardson identified a numerical forecasting method, by a finite-difference grid (Nebeker, 1999; Burstyn, 2008; Christensen, *et al*., 2007).

After introduction of digital computers, better mathematical methods were developed, reducing numerical instabilities in extremely iterative calculations. Digital computers become the core methodology of weather and climate modeling from the 1940s into the present (Burstyn, 2008; Potter, 2009). Immediately after World War II, prediction of weather was among the main applications of digital computers, strongly used and supported by both civilian weather services and military organizations (Potter, 2009).

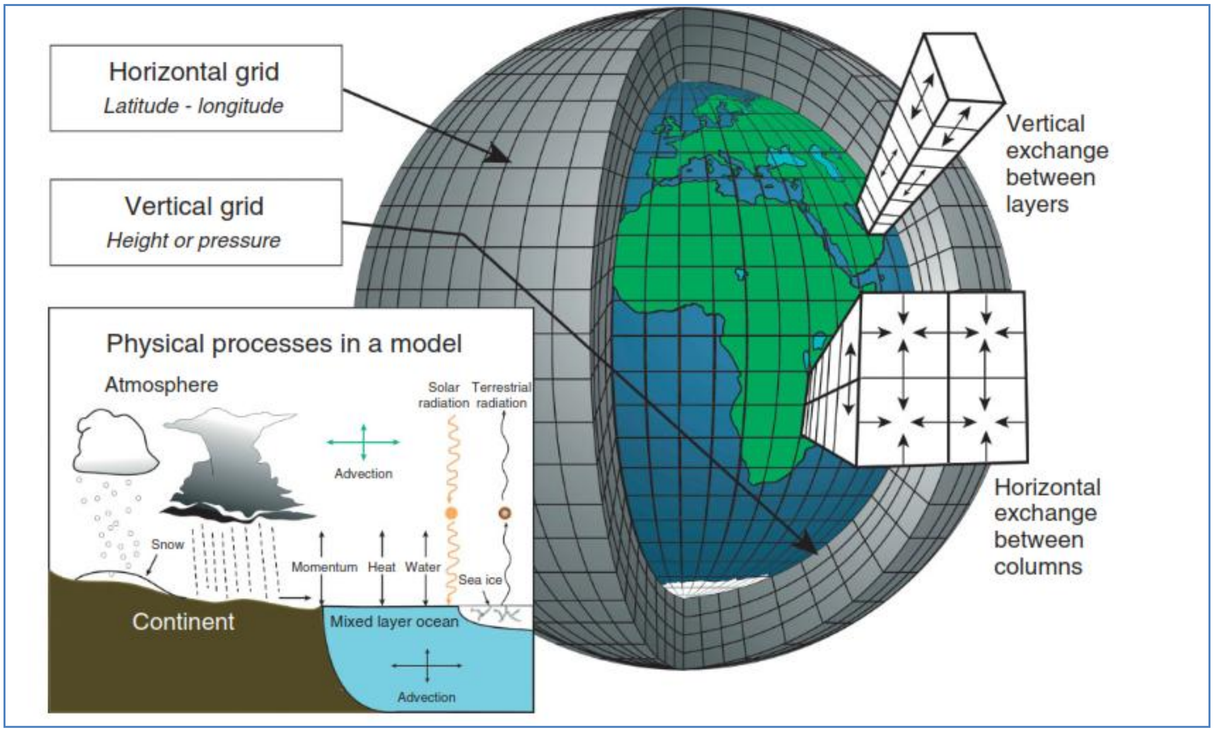


Figure 2.23: Global and Regional Climate Model (RCM) nesting approach. (Source: Edwards, 2011; Trzaska and Emilie, 2014).

Initially computerized experiments of numerical weather prediction (NWP) pursued the method of Richardson's using Cartesian grids (Fig. 2.23) and these methods, compute vertical and horizontal energy transfers and mass between grid boxes on a time step (typically 10 to 15 min) (Edwards, 2011). Early on the models of NWP imposed many easier assumptions in order to decrease the models' computation demands, and all of them were regional not in a global scale (Shackley, 2001; Sundberg, 2007).

The success of NWP lead to efforts to assess the global circulation models over extended periods of time, i.e. to model of atmospheric climate components (Randall, *et al.*, 2007). The Global Circulation Models (GCMs) applied the same techniques as NWP models, however extended these to the global scale. GCMs may be used to simulate climate (Edwards, 2010). The GCMs comprises of 'dynamic components', which simulates large-scale motion of fluids using the equations of motions, and 'model physics', which simulates physical processes such as cloud formation, convection, and radiative transfer (Arakawa, 2004; Petersen, 2006; Sundberg, 2007).

In mid-1955 the first person undertaking a computerized GCM at Princeton's Institute was Norman Phillips (Smagorinsky, 1963; Weart, 2010). He applied budding NWP techniques, completing a 2-layer, hemispheric, quasi-geostrophic computer model. Phillips model simulated surface grids of 10,000 km by 6,000 km, for the circulatory flows and eddies movement. In this model the two pressure levels represented the vertical dimension (Weart, 2010; Trzaska and Emilie, 2014).

GCMs are the most multifaceted tools currently available for simulating the global climate system (Gordon *et al*., 2000; Randall *et al*., 2007). Substantial improvements in the spatial resolution of GCMs have been made, however, a number of challenges still remain (Nimusiima et al., 2014). The challenges are computational costs and challenges in data storage, possible misrepresentation of local and meso-scale climate and hydrological processes.

2.5.2 Evolution of GCMs

In 1956 the United State Weather Center created the General Circulation Research Section. In 1959, United State Weather Bureau invited Tokyo NWP Group to join the laboratory to develop GCM (Smagorinsky, 1963; Manabe and Wetherald, 1975; Edwards, 2011). The first coupled atmosphere–ocean general circulation model (AOGCM) was published in 1969 (Edwards, 2011). Since the 1980s, AOGCMs become increasingly comprehensive. Atmosphere and ocean GCMs, Earth System Models (ESMs) in relation to other climate-related systems such as the land surface, hydrology, vegetation, glaciers, and snow cover are included in these advances. In the meantime, integrated assessment models (IAMs) that were developed, included environmental impact modeling (Hill, *et al.*, 2004).

The propagation of component models led to the opportunity to match and mix for example combining an ocean model from one lab center with a hydrology model from another and an atmospheric model from a third. In response, in 2002 a group including United State National Aeronautical and Space Administration (NASA), United State National Oceanic and Atmospheric Administration (NOAA), United State National Center for Atmospheric Research (NCAR), and United State Department of Defense constituencies began developing an Earth System Modeling Framework (ESMF), essentially a set of software gateways which allow component models to interoperate (Hill, *et al*., 2004).

The information from GCMs may not be realistic for regional and/or national climate change impacts, adaptation and vulnerability assessments because of the high level of uncertainty in GCM simulations due to their coarse grid resolution (typically 2.5 degree latitude by 3.75 degree longitude for the atmospheric components, and 1.25 by 1.25 for the oceanic components) and the misrepresentation of local and meso-scale climate and hydrological processes. GCMs also do not completely include all pertinent local climate processes such as Urban Heat Island (UHI) effects and sea/land breezes (Nimusiima, *et al*., 2014).

Downscaling of GCMs is therefore essential and has been found to reduce the uncertainties associated with GCMs (Williams, *et al*., 2001). The simulations of GCM in the framework of the Coupled Model Inter-comparison Project Phase 5 (CMIP5) for IPCC Fifth Assessment Report (AR5) have used higher spatial resolution and are diverse in their scope and skills (Knutti and Sedlacek, 2012). CMIP5 models include certain Earth System Models, which include chemical interactions, vegetation, aerosols, biogeochemical cycles and ice sheets (Taylor, *et al*., 2012).

2.5.3 Scope of GCMs

GCMs are not only designed to understand climate processes and reproduce observations but they are also used to predict the future climate (Nimusiima, *et al*., 2014). However, the future climate depends upon several factors including anthropogenic activities. As a result, defining the possible pathways of different climate components dictated by their interactions under the influence of internal and assumed external factors (e.g., internal natural and external anthropogenic factors) are important for making future projections. This constraint led to definition of different scenarios under the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathways (RCPs). In the following, a brief review of the GCM experiments conducted under these scenarios is provided.

2.5.3.1 SRES emissions scenarios

The Fourth Assessment Report (AR4) of climate projections for the Intergovernmental Panel on Climate Change (IPCC) were based on four families of emission pathways, A1, A2, B1 and B2 which have been developed from a Special Report on Emissions Scenario (SRES) and simulations called the third phase of the Coupled Model Inter-comparison Project (CMIP3) (Nakicenovic & Swart, 2000; Meehl, *et al*., 2005; McGuffie and Henderson, 2005; Solomon, *et al*., 2009). There are forty scenarios; each makes different assumptions as driving forces like greenhouse gas emission, land-use and others (Moritat, *et al*., 2000).

The A1 scenario family describes coming or future world with very rapid economic growth, characterized by the world population growth reaching its peaks in the mid-century and decline thereafter with the introduction of efficient technologies. Fundamental themes are increased cultural and social interactions and capacity building with a substantial reduction in regional differences in per capita income. The A1 scenario family has three groups that describe alternatives technology in the energy system. They are distinguished by their technological emphasis: a balance across all sources (A1B), non-fossil energy sources (A1T), and fossil intensive (A1FI) (Parry *et al*., 2007; Roe, 2007; Tomassini, *et al.*, 2007).

The A2 scenario family explains a very heterogeneous world. The fundamental theme is independence and preservation of local identities. An increasing of global population and economic development is mainly regionally oriented. Technological changes and per capita economic growth are more fragmented and slower (Parry *et al*., 2007).

The B1 scenario family describes the same global population with convergent world that the highest peaks will be in mid-century and decline thereafter, a high changes in economic structures toward information economy and service sectors with reductions in resource intensity, and introduction of resource-efficient and clean technologies. The emphasis is on solutions to environmental, economic and social sustainability, including improved climate initiatives.

The B2 scenario and storyline family describe the emphasis on local solutions to social, environmental, economic and sustainability problems. The world is continuously increasing global population at a lower rate than A2, levels of economic development will be intermediate, and technological change is less rapid and more diverse than in the B1 and A1 storylines. The scenario is oriented toward environmental protection focuses on local and regional levels (Parry *et al*., 2007).

The uncertainties concerned in SRES scenarios comprises: different options and clarification of storylines by authors, quantification and translation of connections between model inputs and driving forces, differentiation in methodologies engage quality of data use as well as the data sources and emission projections. The SRES scenarios have been assessed critically in relation to natural resource availability, use of economic parameters and production expectations in future (Brohan, *et al.,* 2006). SRES models are outdated having been developed more than 15 years ago. Currently, new emission scenarios developed by the scientific community are in use and these are named as Representative Concentration Pathways (RCPs) (Parry, *et al.,* 2007).

2.5.3.2 Representative Concentration Pathways (RCPs)

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has been carried out using a new set of scenarios that replace the Special Report on Emissions Scenarios (SRES) (Wayne, 2013). There are four pathways: RCP 8.5, RCP 6.0, RCP 4.5 and RCP 2.6. The RCPs are trajectories, based in greenhouse gas emissions, land use changes and aerosols, developed for use by the climate modeling community as a uniform basis for near-term and long-term experiments of climate modeling (Moss, 2010).

The naming practices reveal that socioeconomic pathways will reach a specific radiative forcing by the year 2100 (Gregory and Forster, 2008; Wayne, 2013). RCP 2.6 is mitigation scenarios that assume GHG emissions to decline considerably after 2020 due to an anticipated removal of carbon dioxide from the atmosphere and early involvement from all emitters. RCP 2.6 and RCP 4.5 are modest scenarios in which radiative forcing stabilized by 2100, B1 scenario in SRES is similar to RCP 4.5 (Wayne, 2013). RCP 8.5 assume worst case scenario with the least amount of effort in emissions reductions. A1 scenario from SRES is similar to RCP 8.5 (Wayne, 2013). Observed global model and projected temperature and precipitation analysis show that the B2 and RCP 4.5 scenario projections have greater uncertainty attached to them as stochastic processes and natural variability form a significant part of the results (Riahi, *et al*., 2007).

Appropriate guidance would be to use A2 or RCP 8.5 scenarios in order to obtain a clearer picture of GHG induced changes while using the B1 and RCP 4.5 scenarios to gain indications of the possible ranges of future projections under different emission scenarios (Giorgi and Mearns, 2002; Riahi, *et al*., 2007; Gregory and Forster, 2008).

Table 2.5: Main differences and similarities between temperature projections for SRES and RCPs scenarios with temperature increased till 2100.(Source: The Guide to Representative Concentration Pathways; Wayne, 2013).

RCP	SRES	Particular differences
RCP 4.5	SRES B1	Median Temperature in RCP4.5 rises faster than SRES B1 until mid-century, and slows thereafter.
RCP 6.0	SRES B2	Median Temperature in RCP 6.0 rise faster rise than SRES B2 during the 3 decades between 2060 and 2090, and

		slower on other periods of twenty first century.
RCP 8.5	SRES A1F1	Median temperature in RCP 8.5 rises slower than SRES A1F1 during the period 2035 to 2080 and faster during other periods of 21st century.

The character of RCP 4.5 scenario is that of total radiative forcing, and in turn greenhouse gas concentration will be stabilized after 2100 due to substantial reductions in emissions before 2100. In terms of land use, the use of cropland and grasslands decreases as a result of reforestation programs (Van-Vuuren, 2011). The RCP 8.5 is characterized by continuous increase of greenhouse gas emissions over time. The emissions increase and continue to accumulate resulting in very high GHG concentrations in the atmosphere by 2100. This scenario is energy intensive due to slow technological development and high population growth. RCP 4.5 and RCP 8.5 were selected as bounding range scenarios of anticipated greenhouse gas forcing at a global scale. Similar to the former SRES scenarios, RCPs are a group of scenarios used by climate modelers (Wayne, 2013). Indicators of climate employed in RCPs comprise GHG concentrations and radiative forcing in watts per square meter. The socio-economic process uncertainties are avoided in RCPs. This is because RCPs starts from GHG and radiative forcing. In RCPs adaptation, mitigations and climate policies are all included, making it clear to explore the related impacts. RCPs give detailed GHG concentrations as input variables and data for climate models. In contrast to the SRES scenarios, RCPs represent pathways of radiative forcing but, not in-depth socio-economic narratives or scenarios (Chaturvedi *et al*., 2012). The RCP scenarios process where any single radiative forcing pathway could be derived based on the results from various ranges of technological and socio-economic development scenarios (Riahi, *et al*., 2007).

2.6 Future climate change

2.6.1 Global Context

The global projection for the period 2016 to 2035 which is a near term interval indicates that the global mean surface-temperature is expected to increase between 0.9 to 1.3 °C and predictions for the period 2081 to 2100, which is the long term projection, is an increase in the range from 0.9 to 2.3 °C for RCP-2.6 (IPCC, 2013; Thoeun, 2015). For RCP 8.5 the increase is between 3.2

to 5.4 °C (Fig. 2.24). All values are compared to 1850 to 1900 normal. For the period 2040-2069 the global temperature increases by about 1.5 -2.3 °C based on all RCPs models (IPCC, 2014b). At the global scale the precipitation projection pattern has improved but accuracy is less at regional level and results in less appropriate simulation. Since 1951 the global yearly mean precipitation will increase. Under RCP 8.5 increased precipitation is predicted in high latitudes by 2100; less precipitation will be experienced in many mid latitudes subtropical, semiarid and arid regions including North and South Africa (Fig. 2.25). This is because of natural variability of precipitation and potential influences of land use change (IPCC-WG2, 2014; Thoeun, 2015).

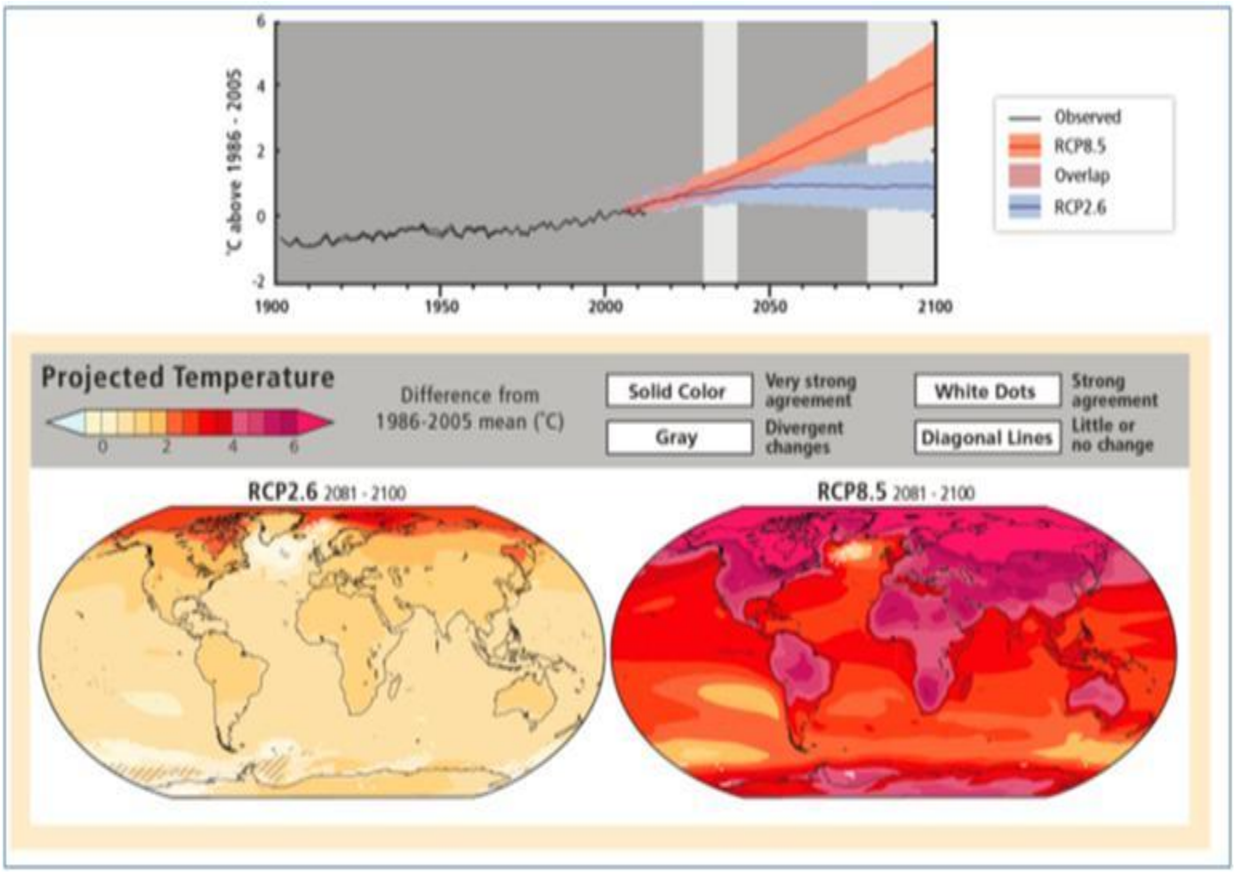


Figure 2.24: Global Projected Temperature describing observed mean global temperature for the period 1986-2005 and projected temperature using RCP 2.6 and RCP 8.5 for the period 2081-2100 (Source: IPCC, 2014a).

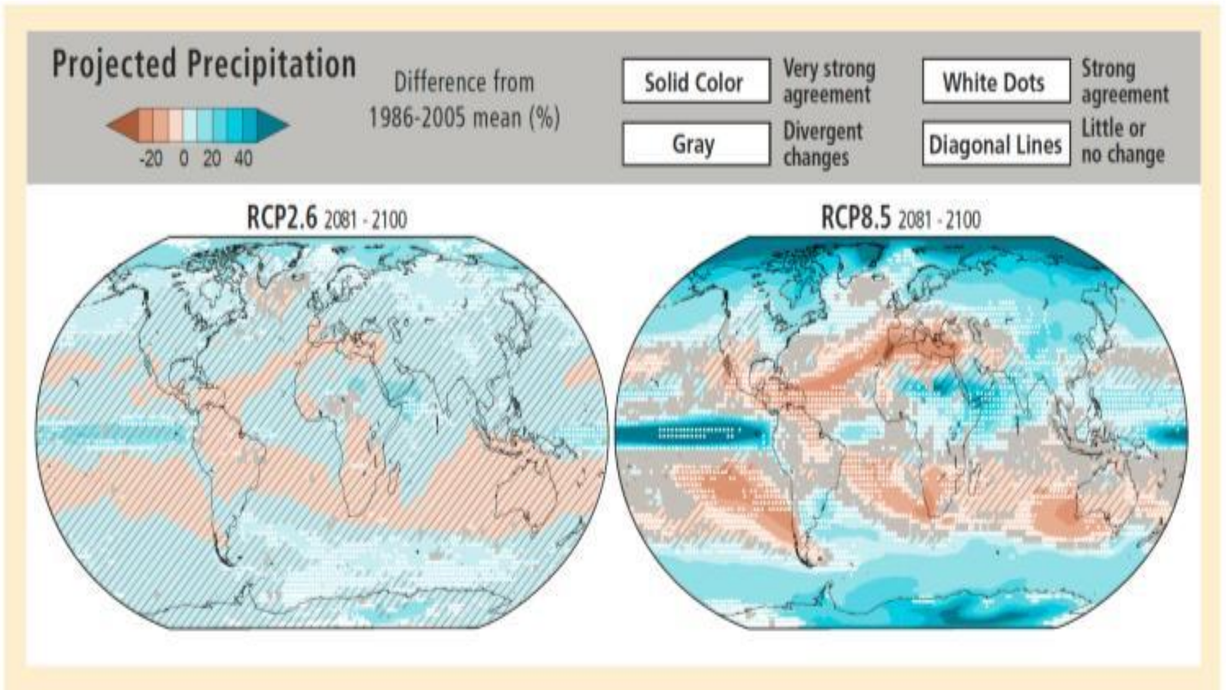


Figure 2.25: Global Projected Precipitation describing projected precipitation difference from the mean 1986-2005 for the projected period 2081-2100 in both RCP 2.6 and RCP 8.5 scenarios (Source: IPCC, 2014b).

A comparative analysis between SRES and RCPs is illustrated in Fig. 2.26. In the twenty first century, by 2100, A2 has a similar route as RCP 8.5 where both will be attaining around 8 Wm^{-2}; and B1 is similar to RCP 4.5 where both project a radiative forcing around 4W m^{-2} (Golden, *et al.*, 2007; IPCC, 2012). In general, global future temperature change with A1B, A1T and B2 projections show substantial differences to that of RCP 8.5 as well as RCP 4.5. The RCP 2.6 mean surface temperature change is around 1 °C which is an increase from the baseline period (see Fig 2.18) (IPCC, 2014b).

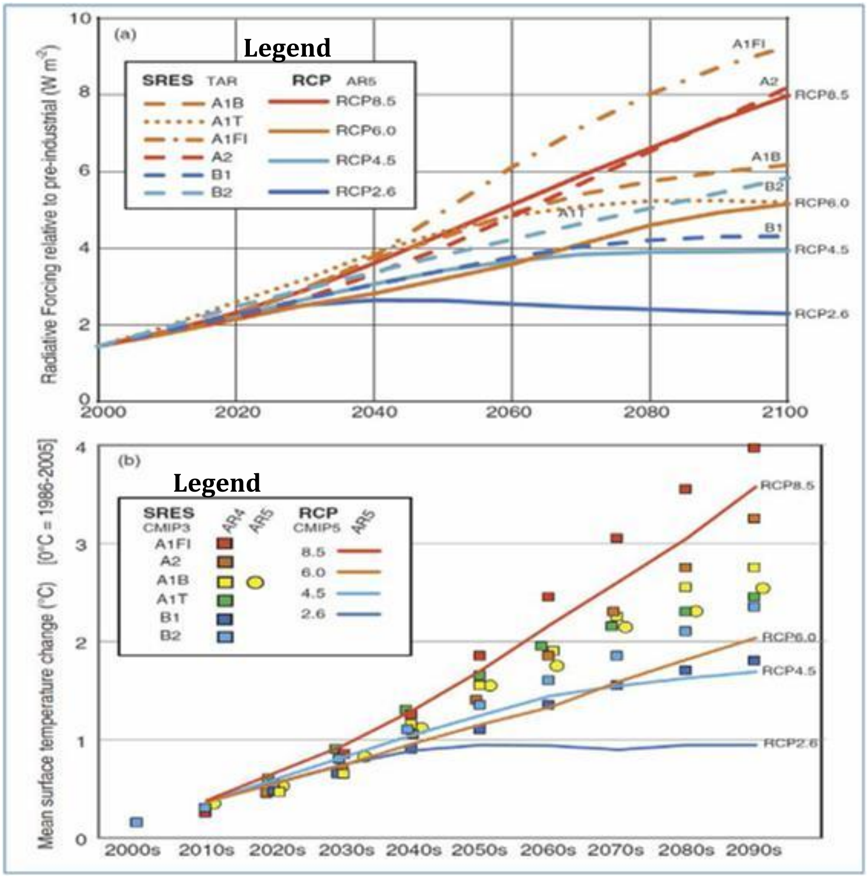


Figure 2.26: Comparison between RCP and SRES Scenarios showing the radiative forcing relative to pre-industrial time for both RCP and SRES scenario and mean surface temperature change from the mean 1986-2005 **(**Source: IPCC, 2013).

2.6.2 Climate Change in African Context

When comparing the annual mean surface temperature of the twentieth century, an increase of 2 °C in both A2 and A1B scenarios is projected for the end of 21st century (IPCC, 2013). Much of the African region, under the RCP 8.5 scenarios, will experience a mean temperature range increase between 3 to 6 °C by the end of the twenty first century. In most arid African regions, the rate of change in minimum temperature will exceed that of the rate of change in maximum temperature. In Northern and South-western parts of Africa a reduction of precipitation is projected for the end of twenty first century under the A2 and A1B scenarios. In East Africa (including Ethiopia) which has complex topography, projections indicate an increase in precipitation and extreme events by the end of twenty first century (Morrison, *et al*., 2009).

2.7 Conclusion

Population growth and climate change are critical problems that the world is facing today. The rate of urbanization at global, regional (e.g., Africa) and country levels is increasing. In Ethiopia and in the city of Addis Ababa the rate is alarmingly high. Urban population increases more in developing countries than in developed regions. Urban areas in the developing world are considerably denser compared to the developed world, and this is to be expected given the correlation between lower incomes and higher population densities.

It is now broadly accepted that climate change is a present day phenomena and further change and variability are inevitable; compared to the past century the average global temperature is increasing. The projected future global mean surface-temperature is also expected to increase for the period 2081 to 2100 from 0.9 to 2.3 °C for RCP 2.6 and from 3.2 to 5.4 °C for RCP 8.5. Projected rainfall changeover sub-Sarahan Africa in the mid- and late 21st Century is uncertain. In regions of high or complex topography such as the Ethiopian Highlands, downscaled projections indicate likely increases in rainfall and extreme rainfall by the end of the 21st Century. The rainfall projection in Ethiopia showed that most lowlands parts of the country (Afar, Somali, and Benishangul-Gumz) will have an increasing rainfall, while in some highland part of the country (Amhara, Western, Eastern, Southern and central Oromia and SNNPR) will experience a decrease in rainfall.

The average mean maximum temperature for the city of Addis Ababa is 24.5 °C, and the average minimum temperature is 12.0 °C. Addis Ababa receives an average of 1255.2 mm rainfall per year. Extreme warm periods in the city of Addis Ababa were observed in the 1990s and early 2000s. For precipitation, the 1970s and 1990s dry period are clearly evident.

This climate information is important in view of the fact that in the world about 87 % of the population gets drinking water from improved sources and the corresponding figure for developing regions is more than 84 %. Access is far greater; however, in urban areas it is about 94 %, while only 76 % of rural populations have access to improved sources. GCMs provide data at coarse spatial scale but down-scaling the GCMs output can provide climate information at local scale to assess the impact of climate on different aspects (e.g., water resources).

This literature review suggests that more work is needed to verify and refine the available climate projections for urban scale in Africa and Ethiopia. Scientist are of the view that since Urbanization in future sub-Saharan-Africa, in general, is uniquely different from the rest of the world, with very complex topography, it is unlikely have subtle atmospheric processes. Therefore, knowing and understanding the historic climate and potential impacts of future climate change at urban scale provide an improved understanding of a host of vital climate processes. Accordingly, it is important that complementary to projections from GCMs, projections from detailed high-resolution regional climate models (RCM) be employed to obtain reliable climate scenarios for the City of Addis Ababa. Precise quantification of impacts and recognition of adaptation strategies both depend on such model products.

CHAPTER 3

DATA AND RESEARCH METHODOLOGY

3.1 Introduction

The research methodology comprises three main phases. The first phase includes obtaining data collected from the Addis Ababa Water and Sewerage Authority (AAWSA) and National Meteorology Agency, Ethiopia. Land-sat images from the U.S. Geological Survey (USGS), Center for Earth Resources Observation and Science (EROS). The reservoir water supply analysis was based on data obtained from the Legedadi-Dire and Gefersa hydrological and meteorological stations (owned by AAWSA). The Bole Airport Station, and Addis Ababa observatory station, provided data for climate baseline data analysis and for downscaling GCM to station level. The second phase involves establishing monthly climatology and trends, downscaling GCM and bias corrections of the resulting climate data for both historic and projection periods. The high resolution WorldClim is used as a reference climatology to produce high resolution data with 1 km^2 grid box for study of urban scale climate. The delta and quantile matching methods are used for downscaling and bias correction respectively.

The third phase entailed the development and application of the above climate change models output in the Water Evaluation and Planning (WEAP) impact model. Potential scenarios within the scope of WEAP model are proposed and utilized to explore plausible outcomes that correspond to the different management options. As such, the planning and management alternatives were conceptualized and processed using WEAP. Finally land use and urban climate change assessment via remote sensing of satellite data and gridded spatial urban climate data are conducted. Arc-GIS and ENVI are used for spatial land use change data analysis.

3.2 Description of the Study Area

3.2.1 Addis Ababa City

Addis Ababa was established in 1889 as the capital of Ethiopia. And located 9° 1′ 48″- 8° 8′ 32″ N Latitude and 38° 44′ 24″- 38° 9′ 05″ E Longitude and situated in the central highlands of the country and covers an area of approximately 526 km^2 with a population of 2.9 million (CSA,

2011) according to population projections made for 2011(AABoFED, 2013). The city is self-governing through a city council. Administratively the city is divided into 10 sub-cities or locally known as Kifle-Ketema which is town division administrations and the total number of Kebele of the city is 116 (see Fig. 3.1). The city administration has different sector bureaus, offices, agencies and authorities. They are responsible for implementing infrastructural development, promoting investment providing economic and social services and performing other regulatory facilities (AACAILIC, 2015). From the total land use of the city, 26 % of the area is residential use while 37 %, 10 %, 9 %, 3 % and the remaining 15 % are used for Green, Road network, Open space, Industrial and different land uses respectively (Abeje, 2012).

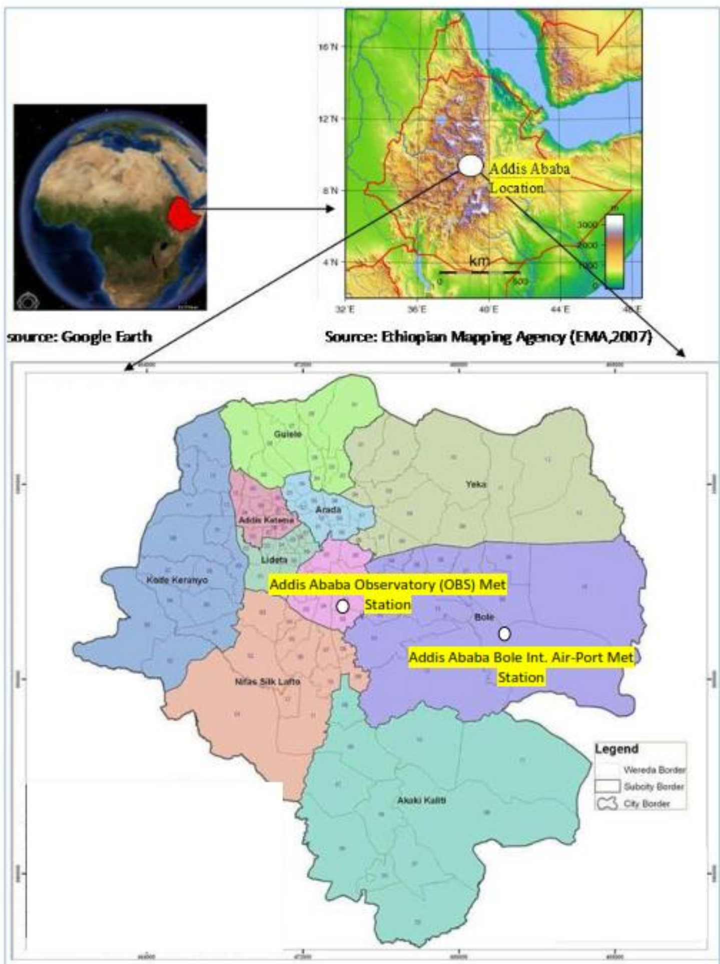


Figure 3.1: Location and map of Addis Ababa. (Source: Addis Ababa City Administration Integrated Land Information Centre (AACAILIC), 2015). Note: Woredas, Sub-weredas, Sefer and Blocks are local names of administrative boundaries under sub-cities.

3.2.2 Water Supply

Water is supplied to Addis Ababa from three dams and about 35 water wells. The water reservoirs for the city are Legadadi and Dire dams, about 30 km Northeast of Addis, Gafersa dam approximately 20 km Northwest of Addis and the Akaki Wells, which is located approximately 10km south of Addis Ababa. All of Addis Ababa's surface water reservoirs are situated in rural landscapes. Legedadi and Dire dams have treatment plants serving an amount of 59,425,092 m^3 per year in 2012 for both domestic and non-domestic water supply activities. The Legedadi treatment plant was recently upgraded in 2015 consequently having an increasing supply and total of approximate 71,175,000 m^3 per year. Gefersa dam reservoir produced 11,306,884 m^3 in 2012 for sub system of Rufael, Core-Kolifie and St. Paul for both domestic and non-domestic consumptions. The wells and spring water supply a total of 41,442,775 m^3 in 2012 for areas of Akaki, Sarries (Central part of Nifas Silk Lafto sub city) and Legedadi West, and non-domestic activity (e.g. industry and other commercial activity). The three water supply dams and catchment areas are shown in Figs. 3.2 All supply dams are located in northern part of the city, and their catchments range from 55.5 to 204.9 km^2.

3.2.2.1 Legedadi dam and its catchment

Legedadi dam catchment area falls within Oromia Regional State under the Administration of North Shoa zone in Aleltu Bereh District. The Legedadi dam was constructed and commissioned in 1970. It is partly constructed of earthen section with a height of 22 meter and crest length of 600 meter. A further section concrete buttress is 44 meter high with a length of 400 meter. The concrete buttress section has overflow spillway gates (AAWSA, 2011).

3.2.2.2 Dire dam and its catchment

The Dire dam was constructed and commissioned in 1998. It is an earthen dam with an un-gated spillway with a height of 22 meter and crest length of 500 m. The altitude in the catchment area ranges from 2,640 to 3,300 meter above mean sea level. The 660 meter elevation difference demonstrates the steepness of the catchment area (AAWSA, 1999). The dam supplies raw water to Legedadi Water Treatment plant via a pipe of (diameter normal in mm) DN 700 Steel for the first 3.6 km and DN 600 Steel for the remaining 3.5 km.

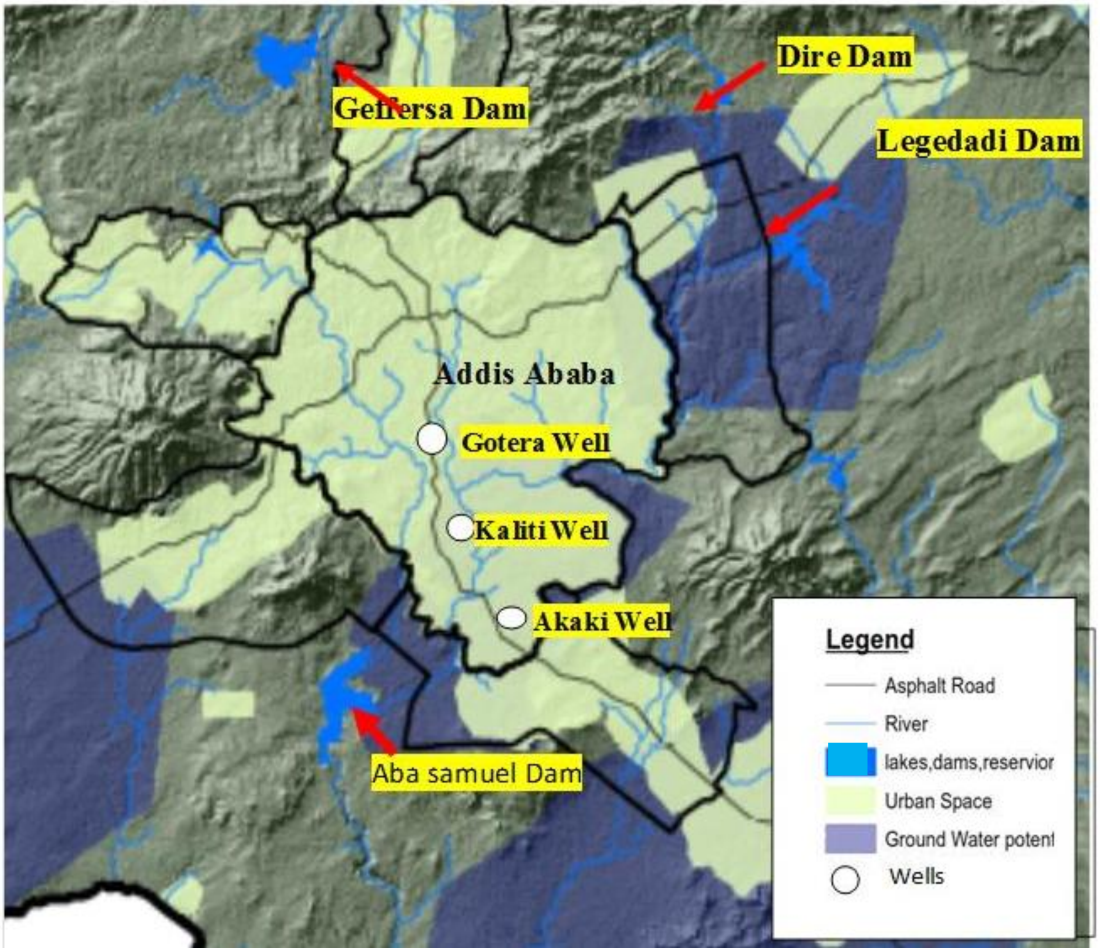


Figure 3.2: Major surface and ground water supply locations (Source: AACPPO, 2014).

3.2.2.3 Geffersa dam and catchment

Geffersa Dam is situated North-west of Addis Ababa. The dam was first developed in 1942 as a masonry structure dam wall with a height of 9.0 meter and after subsequent construction the wall has been raised 3 times. The second height increase was commissioned in 1960 and during the same time a treatment plant was constructed. The third height increase was constructed with earth infill resulting in the total height of 15 meter with a crest length of 220 meter. About 30,000 m^3/day is being abstracted from the dam in 2012. The Geffersa catchment area is 55.56 km^2, or 5,556 ha. The altitude of the catchment area ranges from 2,580 to 2,940 meter above mean sea level. The major physiographic units in this area are undulating plains, valleys, steep stream banks, hills and mountains (AAWSA, 2012).

3.2.2.4 Akaki Well field

Akaki well field is situated southeast of Akaki town and about 22 km south of Addis Ababa. This ground water reserve covers an area of about 16 km^2. A total of 35 wells are drilled within this area: 25 production wells, four monitoring wells, four wells for water supply to Akaki, one well for isotope sampling, and one deep test well. The total average water production from the wells is 46,088 m^3 / day.

3.2.3 Topography

Addis Ababa is mainly classified as flat plains to undulating plains, moderate to high relief hills. These landscapes have distinct geomorphologic features which are categorized by the surrounding Rift Escarpment, and the rivers in the city. Yeka and Gulele sub-cities, in the northern part of the city, consist of hills about 3025 meter above mean sea level descending to 2035 meter above mean sea level at Akaki sub-city in the south, thus the city is, characterized by rugged landscapes and steeper slopes.

3.2.4 Geology

Fig. 3.3 shows recent-basalt (Qb) flows closely associated to the scoria-cones which occur mostly in the area south west of Akaki Kalitiy, Addis Ketema, southern Gulele and northwest of Yeka Sub-cities. These basalt flows together with other similar rocks occurring elsewhere in the city area mainly in fracture zones of the rift escarpment (AACPPO, 2014).

Ignimbrites occur in most part of Bole-Subcity, Kirkos, Northern part of Nifasilk Lafto and southern Yeka Sub-cities (AACPPO, 2014). This forms the Wachacha-Yerer-Furi Group (Tt2). Up to 200 meter thick accumulation of other basaltic unit, mapped in this study as Repi Basalt (Tb3), occurs around most parts of Arada, Kolfe Keranio, Lideta, Southern part of Gulele and Bole sub-cites. Chelelka Basalt (Tb2) is mainly characterized by high degree of fracturing, and penetrated by deep weathering with a gray appearance. Several scoraceous and palaeo soil horizons occur in the unit. Frequent secondary fillings primarily of calcite (amygdules) also occur in open (weathering) cavities of the formation. This rock type is mainly located in the border of Bole and Akakki Sub city and southern Nifasilk Lafto (AACPPO, 2014).

The Mountain Chain of Entoto that surrounds Addis Ababa City from the northwestern, northern and Northeastern directions mainly consists of silicic rocks and grouped as Intoto mixed rocks

(Ti1). It consists primarily of trachytic rocks with some pockets of dacites and rhyolites, occupying major fracture zones along the Northwestern shoulder of the Main Rift System in the area with a trend swinging from the general direction NE to E. Its placement is restricted to the fissure along which it erupted so that little or no flow of the silisic rocks occurs in the area **(**AACPPO, 2014).

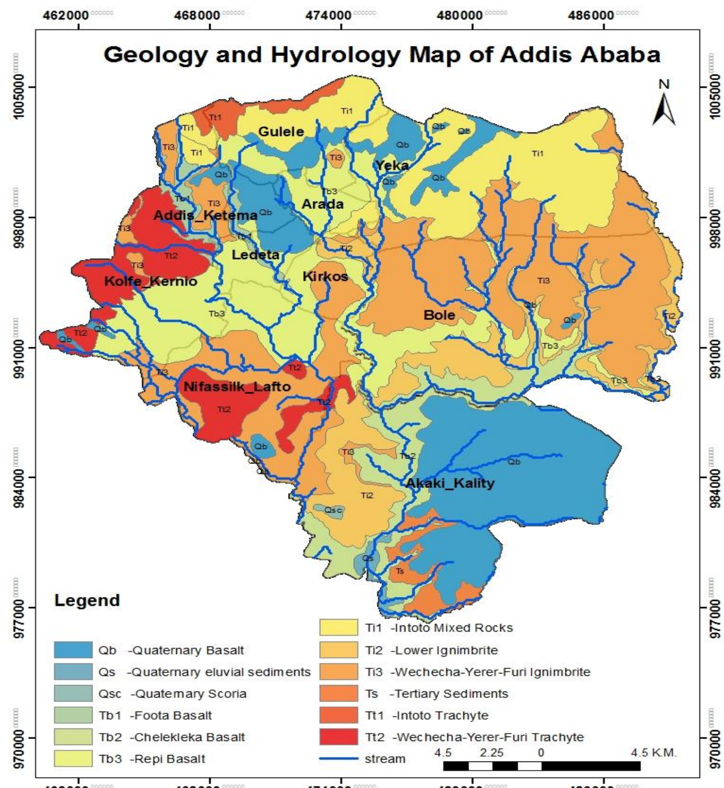


Figure 3.3: Geology map of the city (Source: AACPPO, 2014).

3.2.5 Hydrology

The four water dams namely Aba-Samuel, Legedadi, Dire and Gefersa, and Akaki River, are the main surface water bodies in the vicinity and within Addis Ababa. The River Akaki has main branches which are Little Akaki and Big Akaki rivers. River basin of Little Akaki covers the western part of the city of Addis Ababa (Alemayehu, 2001). While the Big Akaki river basin has various tributaries including Kebena, Ginfile, Bante-Yiketu, Kurtume, Kechene and Yeka are all found within central and eastern part of the city. During Kiremt or long rainy season the city river, streets and drainage becomes cleaner of the city as the runoff takes away the wastes to the south of the city. Although streams and rivers characterized as a self-cleaning resources, most of the city rives are also uses as sewerage lines (Alemayehu, 2001).

3.3 Data

Observed daily and monthly historical data for rainfall, maximum temperature (Tmax) and minimum temperature (Tmin) from two weather stations are used in this study. Stations are Addis Ababa international Airport station found in Bole Sub-city and Addis Ababa Observatory Station (OBS) found in the Addis Ketema Sub-city (Fig. 3.1). The NIMR-HadGM2-AO model data, are obtained from Mengistu Tsidu (2016) (unpublished work), is applied. The downscaled and bias corrected NIMR-HadGEM2-AO model outputs for both present and future periods under RCP4.5 and RCP 8.5 scenarios used, WorldClim reference climatology established from observations for downscaling and used GPCC rainfall and CRU temperatures for bias correction. Special Report on Emissions Scenarios (SRES) of B2 and A2 of HadCM3 model are also employed in this study. The data sets are selected because of their availability (at http://www.worldclim.org/). The HadGEM2-AO model incorporates land use change using Land-use Harmonization (LUH) in the current CMIP5 experiment (Martin et al., 2011; Taylor *et al*., 2012).

Monthly domestic and non-domestic water consumption data found from Addis Ababa Water and Sewerage Authority (AAWSA) are used. Daily water supply data of three reservoirs (Legedadi, Dire and Gefersa) and boreholes (Akaki, Kaliti and Gotera wells) for the year 2012 were collected from AAWSA. These data include monthly inflow, storage capacity, net evaporation and rainfall measured by the stations at reservoirs.

For the land use and land use change assessments, three images were selected; two of which from Land-sat 5 and one from Thematic Map (TM) sensors (USGS, 2016). The Land-sat grid cells size is 30 meter by 30 meter pixel resolution. Elevation, geology and land use data from Addis Ababa City Planning Project Office (AACPPO) was used. For urban climate and the UHI analysis the gridded mean annual rainfall and minimum and maximum temperature for the period 1981-2010 was used. This data range was used because the National Meteorology Agency of Ethiopia could only provide this range (Dinku *et al*., 2011). For future UHI predictions data sets from older emissions scenarios of A2 and B2 from HadCM3 models were analyzed.

WorldClim is reference data used in downscaling climate data which spatially interpolated on grids, are used in many applications, particularly in environmental management (Hijmans *et al*., 2005; Climate Decision, 2008). The worldclim data is useful for urban scale climate interpolation. It is fine resolution and has good capture on topography and other land use variability that may precise with climate gradients. The 1950-2000 WorldClim database is compiled with monthly averages of climate data as observed at weather stations from a large number of local, national, regional and global sources.

The WorldClim climate surfaces have a spatial resolution of 30 arcs which is equivalent to 0.86 km^2. This database is referred to as the 'WorldClim' database. The methods used to explain the uncertainty in both the input data and in the interpolated climate are weather stations elevation biases, quantifications of elevation variations within-grid cell, and the analysis of the result from data screening and cross validation (Hijmans et al., 2005). The WorldClim uses data from global historical climate network of 20,590 rainfall stations and minimum and maximum temperature from 4,966 stations in the world. In the WorldClim all data are adjusted using homogeneity control procedures. The WorldClim climatological normal (CLINO) data used is obtained from (WMO, 1996), and (FAO, 2001).

WorldClim initially intended to include climate data for the 1960-1990 periods only, but it was expanded to 1950-2000 period. The final useful stations were determined only after removing errors. Thus the final database consisted for the precipitation records from 47,554 locations, mean temperature from 24,542 locations, and minimum and maximum temperatures from 14,835 locations. The WorldClim data comparison was made with other previous studies of Daymet and PRISM. The results of Daymet precipitation data are much wetter than WorldClim and PRISM data result shows that much wetter and much drier area than other two. For temperature data WorldClim and Daymet were very similar, and different from PRISM data (Hijmans *et al*., 2005).

3.4 Methodology

3.4.1 Downscaling techniques

Two main techniques of statistical and dynamical downscaling are normally used in climate research (Wilby, 2007). Statistical downscaling methodologies have some practical advantages over dynamic downscaling approaches (Wilby, 2007). In a state where rapid assessments of local climate change impacts are required, the statistical method is a more promising option. SDSM Version 4.2 was supported by the Environment Agency of England and Wales as part of the Thames Estuary 2100 project. Assessments typically group downscaling methodologies into four types: a) dynamical climate modeling, b) synoptic weather typing, c) stochastic weather generation, or d) transfer-function approaches.

a) Dynamical climate modeling

Dynamical downscaling implies as the shell of a higher resolution Regional Climate Model (RCM) within a rough resolution GCM. The RCM uses the GCM to define time–variation atmospheric boundary conditions around a limited domain, within which the physical dynamics of the atmosphere are modeled using horizontal grid areas of 20 to 50 km. The main limitation of RCMs is that they are as computationally complex as GCMs (space constraints on the possible domain size, number of tests and duration of simulations). The RCMs main advantage is that it can resolve smaller scale atmospheric features such as orographic precipitation improved results than that of the host GCM. Additionally, RCMs can be used to investigate the relative impact of different external forcing such as terrestrial–ecosystems. Downscaling dynamically involves nesting a Regional Climate Model (RCM) into a GCM which provides boundary as well as initial lateral conditions (Christensen *et al.*, 2007). Dynamical downscaling can simulate local feedback features which may not be captured by statistical methods however it requires substantial computing resources (Trzaska and Emilie, 2014). Statistical downscaling on the other hand involves finding statistical relationships between global scale features from GCMs and fine resolution climate for a particular location requiring less computing resources to supplement dynamical downscaling (Mahmood *et al*., 2014; Williams *et al*., 2011).

b) Synoptic weather typing

Weather typing involves the grouping of local weather phenomena and meteorological data in relation to prevailing atmospheric circulation patterns. Scenarios of climate change are constructed, either by re-sampling the observed data distributions (which is conditional on circulation patterns produced by a GCM), or by generating synthetic sequences of local weather patterns and then re–sampling data from the observed stations. Weather pattern downscaling is found to be sensible linkages between weather at the local scale and climate on the large scale. It is a valid technique for a multi–site applications and a wide variety of environmental variables. However, weather typing system can be constricted, forming a poor basis for downscaling sporadic or unusual events, and being completely dependent on stationary circulation to surface climate relationships. Possibly, the most serious limitation is that rainfall changes produced by changes in weather patterns frequency are hardly in consistent with the changes produced by the GCM (except when additional predictors such as atmospheric humidity are employed) (Wilby *et al*., 2007).

c) Stochastic weather generators

The stochastic downscaling approaches will involve the modification of the parameters from conventional weather generators such as Long-Ashton-Research-Station-Weather Generator (LARS–WG) or Environmental Agency Rainfall and Weather Impact Generator (EARWIG). The model simulates using two states for precipitation occurrence, first Markov-chains: precipitation amounts on wet days using a gamma distribution; temperature and radiation elements using first order trivariate auto-regressions that are conditional on precipitation occurrence. Stochastically climate change scenarios are produced using revised parameter sets scaled in line with the outputs from a host GCM. The main benefit of this technique is that it can exactly reproduce many observed climate statistics and has been broadly applied, mainly for impacts on agriculture. Stochastic weather generators also allow efficient production of large ensembles of scenarios for risk analysis. The key shortcoming relate to the reproduce annual to decadal climate variability, and the unexpected effects that changes in precipitation occurrence may have on secondary variables such as temperature (Mahmood, 2014).

d) Transfer-function approaches

Downscaling of Transfer-function methods applies empirical relationships between regional scale predictor(s) and local scale predictands. Each downscaling schemes differ according to the choice of predictor variables or statistical fitting procedure and mathematical transfer function. Linear and non–linear regression can be used to derive predictor–predictand relationships. The main potential of transfer function downscaling is the relatively ease of application, coupled with their use of observable trans-scale relationships. The main weakness is that the models explain only a fraction of the observed climate variability (mainly in precipitation series). The weather transfer methods also assume validity of the model parameters under future climate scenarios and the downscaling is very sensitive to the choice of predictor variables and statistical form (Mahmood, 2014).

3.4.1.1 Local Climate Downscaling Using SDSM

The SDSM runs involve: 1) quality control and data transformation; 2) screening of potential downscaling predictor variables; 3) model calibration; 4) generation of ensembles of present weather data using *observed* predictor variables; 5) statistical analysis of observed data and climate change scenarios; 6) graphing model output; 7) generation of ensembles of *future* weather data using GCM–derived predictor variables (Wilby & Dawson, 2007).

The SDSM used in this study is version 4.2.9. The predictor data sets are obtained from the GCM grid equivalent to the study area of Addis Ababa city. The predictand is a large series of observed daily data (precipitation and maximum and minimum temperature) at the OBS and Bole Airport meteorological stations representing the city area of Addis Ababa. The predictor data supplied by the user are from National Centre for Environmental Prediction (NCEP) and UK Met Office's Hadley Centre model version 3 (HadCM3). SDSM uses a set of parameters, relating the predictors to the predictand, for deriving local current and future weather data, based on the output of the GCM time periods.

The SDSM has been found to have some limitations in downscaling daily precipitation amounts at individual stations. This is due to the generally low predictability of daily precipitation amounts at local scales by regional forcing factors. This unexplained behavior is currently modeled stochastically (within SDSM itself) by artificially inflating the variance of the downscaled precipitation series to correspond with daily observations. This current study used SDSM to downscale future climate projection for Addis Ababa under older emission scenarios. The study employ the Special Report on Emissions Scenarios (SRES) in particular A2 and B2 emission scenarios. These emission scenarios are chosen based on both an adequate coverage of study area's future economic evolution, and data availability.

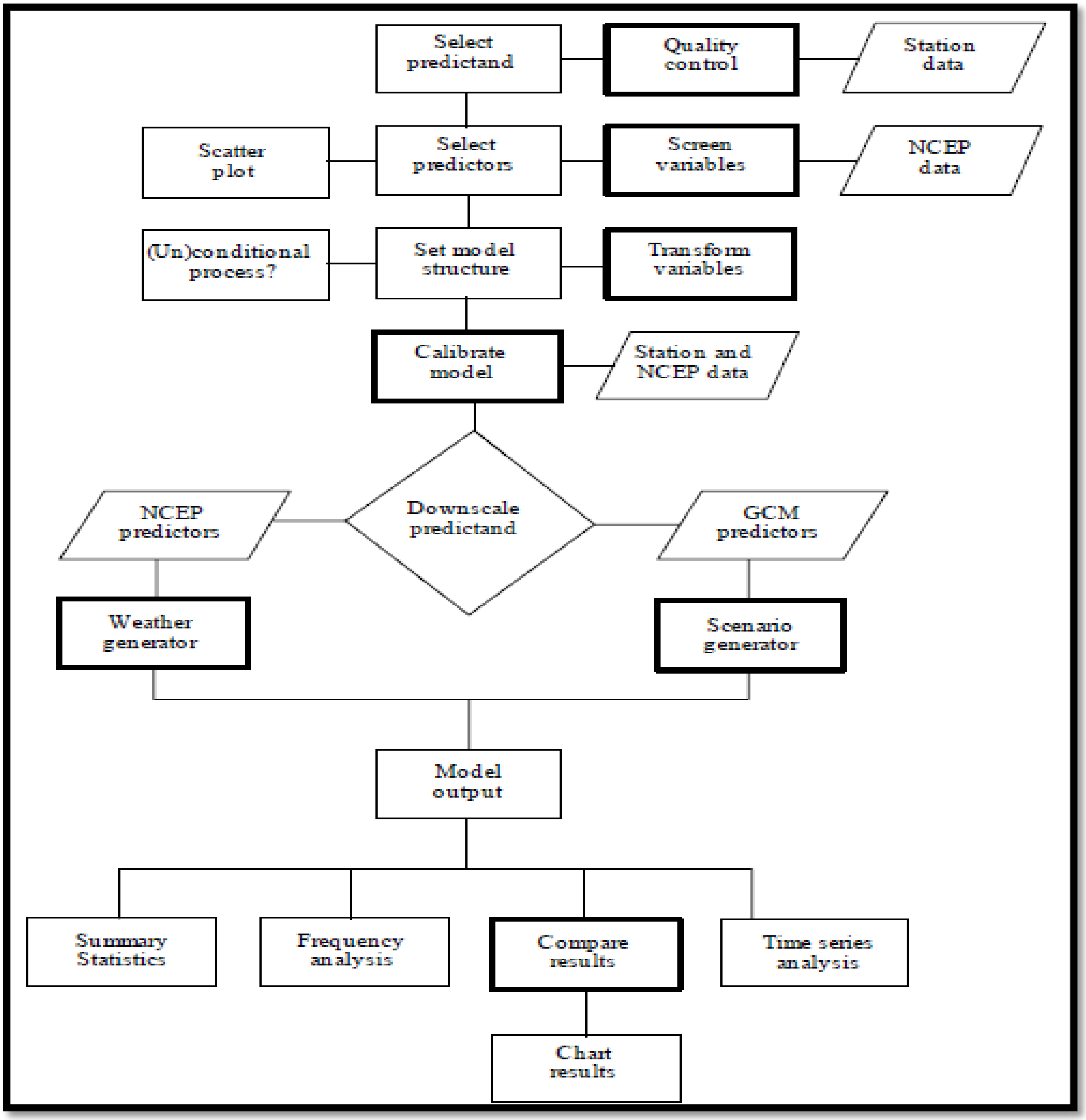


Figure 3.4: SDSM climate scenario generation (Source: Wilby *et al*., 2002).

3.4.2 Water Evaluation and Planning (WEAP) Model Development Scenario

The Stockholm Environment Institute (SEI) developed Water Evaluation and Planning (WEAP) model in 1988 and involved in continuously updating the WEAP model to make it suitable for use in planning, evaluation and management for water resource development. WEAP model is a sensible integrated model for development of water supply, based on various uses of water demand. These practical tools enables the integration of water demand planning and allocation planning on equal footing to determine water supply variability, in both space and time.

The WEAP model is able to simulate a broad range of engineered and natural components of water systems, including rainfall runoff, in-flow and recharge of groundwater from precipitation; water conservation; water demand analyses, hydropower generation; reservoir operations; water quality and pollution tracking and vulnerability assessments. Various scenarios can be planned to explore the potential of future impacts and effects of changes in water supply, stream-flow, runoff (e.g. water recycling, land use change, climate change) and water demand (e.g. population growth, economic development) (Pauw *et al*., 2011; Mounir and Ma, 2011).

The WEAP model also provides a flexible and comprehensive framework for (i) policy analysis and (ii) a system for maintaining water supply (iii) demand information (SEI, 2007). The WEAP model is specifically effective as a predictive tool, while it effectively simulating water demand, supply, flow and storage. The WEAP model work is based on the municipal water balance systems. Also, the WEAP model simulates a wide-range of runoff catchment flow, and recharge of groundwater from rainfall, supply and demand analysis, and water quality. As such, the WEAP model is essentially a tool for the management and analysis for the planning of water supply options. *What if scenario* planning such as *what if* climate (rainfall pattern) changes? *What if* population is increasing? e.t.c. can be effectively explored. Rochdane *et al*. (2012) used the WEAP model to develop a water demand adaptation strategy for the water supply and demand of Morocco from the Rheraya Watershed under specific impacts of climate change. The study used different scenarios of socio-economic development and climate change to analyze future water supply; in particular, population growth, GDP, and rainfall for the region.

Harma *et al*. (2012) developed scenarios analyzing the relationship of future water supply and demand with land use, population growth and climate in the Okanagan Basin of British Columbia, using the WEAP model. The study indicated that change in climate and land use altered the water demand in the Basin. The results from the study indicate that expected change to future climate conditions will reduce river flow when assessed with population growth. The storage systems under the Okanagan basin scenario analysis are shown to lack capacity to meet the growing population during the projected 2050s period. The subsequent adaptation mechanism used in the Okanagan Basin is to improve water supply through demand side reductions. The study also demonstrates a method of integrating knowledge from the fields of climate science, forest hydrology, water systems management and stream ecology to aid in water and land management decision-making. Mccartney & Arranz (2007) also used the WEAP Model to identify upcoming water demands in the Olifants basin, in South Africa and found that increasing population and high demand of water in rural areas, as well as the mining activities and new power plants cooling, increase the complexity of water resources management.

The WEAP model defined two different intervals of time: the "Current Accounts" and "Forecasting period". The "Current Account" represents the basic definition of the water system as it exists, and forms the foundation of all the scenario analysis. These elements will include the main reservoirs; (i.e. surface water reservoir of Legedadi, Dire and Gefersa) and ground water in the Akaki reservoirs and springs. These reservoirs are fed by surface water and wells as shown in Chapter 5. The monthly inflow, storage capacity, and net evaporation for each reservoir are calculated. The main demand nodes considered the surface and underground water abstractions for domestic, commercial and industry water supply areas: For this study eight customer distribution centers in the city are identified as demand nodes.

3.4.3 Land use Change Impact and Urban Heat Island (UHI) prediction

The land use change detection is based on land classification. Data loading, geo-referencing and merging of remote sensing data with observed classification output statistically generated were the major tasks in land use change detection. ENVI 4.3 software was used for processing the remote sensing images and Arc-Map10.2 data was used for land cover change detection. Method proposed by Anderson et al., 1976; was used for land use classification. For vegetation cover assessment, the normalized differencing vegetation index (NDVI) was used (Birkneh, 2007). For nocturnal minimum temperature difference between urban center and nearby rural meteorological observation station (u-r) and urban heat island (UHI) prediction assessment, the statistical variables relationships were developed SDSM. The predictors of large scale indices were obtained from the NCEP reanalysis for the current climate.

3.5 Conclusion

In this chapter the study area is described. The water supply areas are also indicated in hydrological map of the city. The topography and geological characters of the city are described. Data and the methods used to analyze the data are discussed. The detailed methodologies for analysis are described in the respective chapters of this current study. Remote sensing data is used for land use change detection. A brief description of climate models used and procedures to downscale them to higher spatial resolutions are discussed. Statistical downscaling tool, SDSM, and application model, WEAP, are described in this chapter. In summary, the methods that were employed were intended to provide an understanding and reflection of the climatic effects of urbanization and land use change as well as the effect of climate change on water supply and demand in the study area.

CHAPTER 4

PRESENT AND FUTURE SIGNATURE OF CLIMATE CHANGE AT AN URBAN SCALE

4.1 Introduction

The most recent assessment shows that most of Africa is likely to warm during this century, with the drier subtropical regions warming more than the moist tropics (Huntington, 2004; IPCC, 2013). This change in the physical environment and urban growth thus suggests that the water supply of plants influences the air, plant nutrient status of soil and biological activity (Eriyagama *et al*., 2010). Projecting future changes are rather difficult, due to the uncertainties in the forecast of global and long-term precipitation and temperature patterns (including their temporal and spatial variability) in combination with the changing hydrological cycle such as alterations in precipitation patterns, soil moisture conditions, surface runoff, river flow and discharge (Brohan *et al.,* 2006; Várallyay, 2010). Therefore, knowledge and understanding of historic and future climate change at urban scale gives an improved advantage of climate processes enabling more accurate adaptation responses (Eriyagama *et al*., 2010; Tabari, *et al*., 2016).

The objectives of this chapter is to asses and present the current and future change in climate for the city of Addis Ababa and its surrounding catchment using observations and downscaled data from the Global Circulation Model (GCM).

Specific objectives are:

- To assess observed climate change (1950-2000), calibrate the GCM model data output, correct the bias for the rainfall and temperature separately using predictor variables from the NCEP data set.
- To understand spatial variation of urban climate using HadGEM2-AO model output for present conditions and future climate under RCP 4.5 and RCP 8.5.

- To identify possible climate change signal in the historic and future precipitation, maximum and minimum temperatures maps for the Addis Ababa and surrounding areas using HadGEM2-AO model output and HadCM3 outputs.

Section 4.2 below this chapter describes the data selection, methods used for analyzing the historic and projected climate data for evidence of climate change. Section 4.3 presents the result and discussion followed by the conclusion in Section 4.4.

4.2 Data and Methodologies

4.2.1 The Baseline Climate

The standard climate period of reference defined by World Meteorological Organization (WMO) is called a "climate ‘baseline" (WMO, 2008). This is about a thirty-year period which is referred as the “normal” period. Usually modeled future climate change is calculated using the baseline as reference periods (IPCC, 2001). Creating baseline periods are fundamental for assessing upcoming impacts of climate change and to obtain quantitative values for expected change in climate.

4.2.2 Climate Scenarios selection

Emission scenarios are defined by IPCC (2000) as alternative future climate functions. They are alternative scenarios informing how future climate scenarios are revealed. However, they are not predictions or forecasts (Nakicenovic & Swart, 2000). Climate scenarios should be consistent and representative for future climate projections (IPCC, 2013). There are four possible criteria to use for impact assessment for policy makers. Based on IPCC (2013) report, the global projection criteria’s are: (1) applicability for the assessment of the impacts, (2) physical, (3) accessibility and (4) representativeness. Due to the coarse spatial resolution of the UK Met Office's Hadley Centre Global Environmental Model version 3 (HadCM3), Statistical Downscaling Method (SDSM) is used to derive future and current local climates for the study area. SDSM enables the construction of climate change scenarios for Addis Ababa city observational station site at daily time scales, using a the nearest grid location to the study area of Addis Ababa (Y= 31 and X= 11 or Latitude: 10.0 °N and Longitude: 37.50 °E). The WorldClim data is of a high spatial resolution (about 1 km^2) and this global climate set consists of layers which are suitable to assess the climate of urban areas (Hijmans et al., 2005). Therefore, WorldClim data is used as reference climatology for the 1950-2000 periods for downscaling NIMR-HadGEM2-AO to the same spatial resolution.

4.2.3 Data selection

Observed daily and monthly historical data for rainfall, maximum temperature (Tmax) and minimum temperature (Tmin) at Addis Ababa Observatory station (9.01 °N, 38.74 °E) and the gridded 1 km^2 resolution observed data set from Worldclim is also used as a baseline data after validation with station observation. The NIMR-HadGM2-AO model data is obtained from CMIP5 data server and downscaled using delta method for RCP 4.5 and RCP 8.5 scenarios (obtained from Mengistu Tsidu, 2016 unpublished work) as well as data sets from the Special Report on Emission Scenarios (SRES) B2 and A2 of the HadCM3 model are also employed in this study. The data sets are selected because of their availability.

4.2.4 Methodologies

For observed and projected rainfall, maximum temperature (Tmax) and minimum temperature (Tmin) data, the analysis applied using the anomaly or change to examine the temporal characteristics of climate variability and determine the temperature characters and prevalence of droughts, excessive rainfall, over the observed and projected period. Rainfall anomaly was computed as:

$$RFA_i = \left(\frac{RF_{i-RF_\mu}}{RF_\mu}\right) \times 100 \qquad \text{Eq. (4.1)}$$

where, RFA_i is anomaly of rainfall for i^{th} year; RFi is annual or monthly rainfall for i^{th} year and RF_μ is long term mean annual or monthly rainfall, the value is multiplied by 100 to determine the percent of change.

Meteorological drought is negative rainfall anomaly or below the long term mean, which is defined as a percentage reduction from the long term average annual or seasonal rainfall (Keyantash & Dracup, 2002; Wilhite, 2000).

It is deemed inappropriate to use GCMs spatial resolution to provide features that are important to study climate impact at regional and local scale (Wayne, 2013). To avoid such restriction, it is

common to use downscaled data from GCMs (Parry, *et al.*, 2007; Taylor *et al*., 2012; Martin *et al*., 2011). One of the techniques in climate downscaling is the statistical downscaling method.
The SDSM uses multiple linear regression (MLR) techniques to allow spatial downscaling of daily predictor-predictand relationships (Wilby *et al.*, 2002). The predictors which total twenty six from both NCEP and HadCM3 (H3-A2 and H3-B2) were obtained from the Canadian Climate Scenarios for the periods of 1961 to 2001 and 1961to 2099 (Semenov & Barrow, 2002; Samadi *et al*., 2012). H3-A2 and H3-B2 are the IPCC emission scenarios A2 and B2 of HadCM3 respectively (Nakicenovic & Swart, 2000). The NCEP predictors are first interpolated to grid cells of 2.5° × 2.75° resolution of HadCM3 (Wilby *et al*., 2002). The historical and the projections climate data are then downscaled to station level using SDSM. Consequently, the predictors of NCEP and HadCM3 were normalized utilizing standard deviations and long-term mean of the period 1961– 1990. The normalized predictors for HadCM3 are in such format that can be downloaded according to the coordinates of the study areafor direct use in SDSM (Wilby *et al*., 2002).

The MLR enables statistical relationships between large-scale variables (e.g., from NCEP) and local-scale variables, (e.g., data at point level from observations at a station) to produce some parameters of regression (Hashmi *et al*., 2009; Lansigan & Salvacion, 2007). These parameters which are calibrated, along with GCM predictors and NCEP, are used by stochastic weather generation to simulate daily time series and create a correlation with the observed time series.

4.2.4.1 Predictors Screening

The techniques of statistical downscaling involve establishing empirical relationship between larger scale atmospheric variables that include the predictor and predictand (Khan *et al.*, 2006). Therefore, in this method, the predictand verse predictor relationship can be given as:

$$R = F(x) \qquad \text{Eq. (4.2)}$$

where R is predictand, the downscaled local climate variable, x is the predictor, which are climate variables of large scale and F is a stochastic function that relates to the above mentioned two variables (Khan, *et al.*, 2006). The atmospheric forcing variables (see Table 4.1) are obtained from the SDSM data archives.

Table 4.1: Predictor variables for SDSM calibration and HadCM3 time periods (Khan, *et al.*, 2006).

Dataset	Description
Calibration	The 50 years of predictor data (1950-2000) resulting from the data set reanalysis of National Centre for Environmental Prediction (NCEP), USA.
H3A2a - current and H3B2b - current	Contains daily data sets of 139 years predictor of GCM data from HadCM3 A2 & B2 with resolution 2.5° x 2.75°
H3A2a - 2030s and H3B2b - 2030s	2010 to 2039 daily output from the HadCM3 A2 & B2 experiments.
H3A2a - 2050s and H3B2b - 2050s	2040 to 2069 daily output from the HadCM3 A2 & B2 experiments.
H3A2a - 2080s and H3B2b - 2080s	2070 to 2099 daily output from the HadCM3 A2 & B2 experiments.

As part of downscaling, a blend of the partial correlation and correlation matrix are used. To choose the most suitable large scale parameter is not difficult, however, the selections of a second, third, fourth, and so on are prone to subjectivity. The predictor variables that are highly correlated with predictand (and are statistically significant, low p value, $p < 0.05$) are selected. The model was processed using an unconditional process for the temperature, and a conditional process for precipitation depending on wet-day occurrence.

4.2.4.2 Quality control and data transformations during SDSM procedure

The default model settings as specified by Wilby, *et al*. (2002) was used in all the quality control checking steps, except for the observed daily precipitation, where a 4^{th} root model transformation and variance inflation were applied. The two procedures allow precipitation values are to have normal distribution and to have less skewed distribution to low precipitation values (Wilby *et al*. 2002). A summary of the quality control results and modified model settings are presented in Table 4.2.

Table4.2: Quality control setting.

Controls	Rainfall	Temperature Max/Min
Total Values	14958	14875/14880
Missing Values	0	0
Bias Correction	1	1
Variance Inflation	14	12
Transformation	4^{th} root	-
Event Threshold	0.5	0

4.2.5 Calibration of SDSM and selection of predictor variables

From the twenty-five NCEP variables, only a few were used as the predictand variables (see Table 4.3). In this downscaling a blend of the partial correlation, *P* value and correlation matrix are used. Choosing the most suitable large scale parameter is simple; however, the selection of the second, third, fourth, so on is subjective. Therefore, a quantitative procedure is applied for screening large-scale variables for every local-scale variable at each observed climate stations (Mahmood and Babel, 2014).

Monthly regressions of the predictors with the predictand variable are run, a correlation matrix and explained variance are produced, and the predictor variables that are the most correlated with the predictand (and are statistically significant, low p-value, $p < 0.05$) are selected. The model was run using an unconditional process for temperature and a conditional process for precipitation dependent on wet-day occurrence.

The results of the variable screening analyses show that the 500 hPa meridional velocity variables (ncepp5_vaf), relative humidity at 500 hPa (ncepr500af), relative humidity at 850 hPa (ncepr850af) and near surface relative humidity (nceprhumaf) are more suitable in predicting the precipitation. The near surface relative humidity is observed to be a useful predictor variable, followed by relative humidity (RH) at 500 hPa and RH at 850 hPa respectively (see Table 4.3).

The Addis Ababa Observatory station maximum and minimum observed temperature were modeled successfully from the HadCM3 since mean sea level pressure, surface vorticity, 500 hPa geo-potential height and 500 hPa Geo-potential Height are successfully used to downscale the two temperatures through the study period irrespective of season.

Table4.3: Calibration result between Predictand and Predictors.

Addis Ababa OBS Station				**Addis Ababa Bole Station**			
Pridictand	**Predictors**	**Partial *r***	***p* -Values**	**Pridictand**	**Predictors**	**Partial *r***	***p* -Values**
Rainfall	ncepp_faf .dat	-0.054	0.000	**Rainfall**	ncepp_faf.dat	-0.077	0.0000
	ncepp8_v af.dat	-0.041	0.004		ncepp_vaf.dat	-0.039	0.0251
	ncepr500 af.dat	0.03	0.045		ncepp.dat	0.044	0.0012
	ncepp8zh af.dat	-0.037	0.012		ncepp8zhaf.dat	-0.045	0.0102
Min Temp.	ncepp_faf .dat	0.072	0.000	**Min Temp.**	ncepmslpaf.dat	0.068	0.0000
	ncepp_va f.dat	-0.109	0.000		ncepp5_faf.dat	-0.069	0.0000
	ncepp_za f.dat	-0.182	0.000		ncepp5zhaf.dat	-0.031	0.0005
	nceptemp af.dat	0.37	0.000		ncepp850af.dat	-0.053	0.0000
					nceptempaf.dat	0.134	0.0000
Max Temp.	ncepmslp af.dat	0.029	0.001	**Max Temp.**	ncepmslpaf.dat	0.065	0.0000
	ncepp_faf .dat	-0.119	0.000		ncepp_vaf.dat	0.093	0.0000
	ncepp_va f.dat	0.316	0.000		ncepp5zhaf.dat	-0.023	0.0134
	ncepp_za f.dat	-0.048	0.000		ncepp850af.dat	-0.069	0.0000
	nceptemp af.dat	0.148	0.000		nceptempaf.dat	0.119	0.0000

4.2.6 Bias Correction

Bias corrections are applied to the down scaled data (Salzmann et al., 2007). The bias correction methods, used in this study are:

$$T_{deb} = T_{SCEN} - (\overline{T_{CONT}} - \overline{T_{obs}}) \qquad \text{Eq. (4.3)}$$

$$P_{deb} = P_{SCEN} \times \left(\frac{\overline{P_{obs}}}{\overline{P_{CONT}}}\right) \qquad \text{Eq. (4.4)}$$

where T_{deb} and P_{deb} are daily time series of corrected temperature and precipitation for future periods while SCEN represents the downscaled scenario data for the future periods (e.g., 2011–2099), and CONT represents downscaled data for the observed period (e.g., 1950–2000). T_{obs} and P_{obs} represent observed temperature and precipitation data for the period (1950-2000). The bar on T and P shows the long-term average. The monthly mean of 50 years (1950-2000) are deducted as given in Eq. (4.3) for temperature. For precipitation long-term observed monthly mean rainfall data is divided by simulated as shown in Eq. (4.4). The major underlying assumptions are that the frequency and intensity of rainfall are the two main factors affecting rainfall variability (Wilby, *et al*., 2002). Therefore, the application of this method is to correct the precipitation amount and not the frequency with the assumption that frequency is accurately simulated by SDSM and also to remove any systematic errors belonging to SDSM during downscaling. The assessment of climate change over the city is based on four climate periods, namely: baseline climate and climates of the 2030s, 2050s and 2080s (Wilby, *et al*., 2002).

4.3 Results and Discussion

4.3.1 Observed mean climate and comparison with gridded global Worldclim data over the city of Addis Ababa

Temperature data recorded for Addis Ababa City for the period 1965 to 2009 is presented in Fig. 4.2 using trend analysis of maximum and minimum temperature anomalies compared from the baseline mean 1971-2000 at Addis Ababa Bole International Air-port (AABIA) and Observatory stations (AAOBS). Significant warming of minimum temperatures at Addis Ababa Observatory and Bole Airport station are observed in the period between1965 to 1983, but the warming in the inner parts of the city (i.e., Addis Ababa Observatory station) is higher than that at the rural station (i.e., AABIA) for both minimum and maximum temperatures. The increase in the maximum temperature is larger than that of the minimum temperature, and the trend in minimum temperature change for Addis Ababa Bole Airport and Observatory (OBS) stations is 0.19 °C and 0.47 °C per decade, respectively (Fig. 4.1a). The warming trend in maximum temperature (Fig. 4.1b) for Addis Ababa Bole Airport station and Addis Ababa Observatory Station is 0.27 °C and 0.55 °C per decade, respectively.

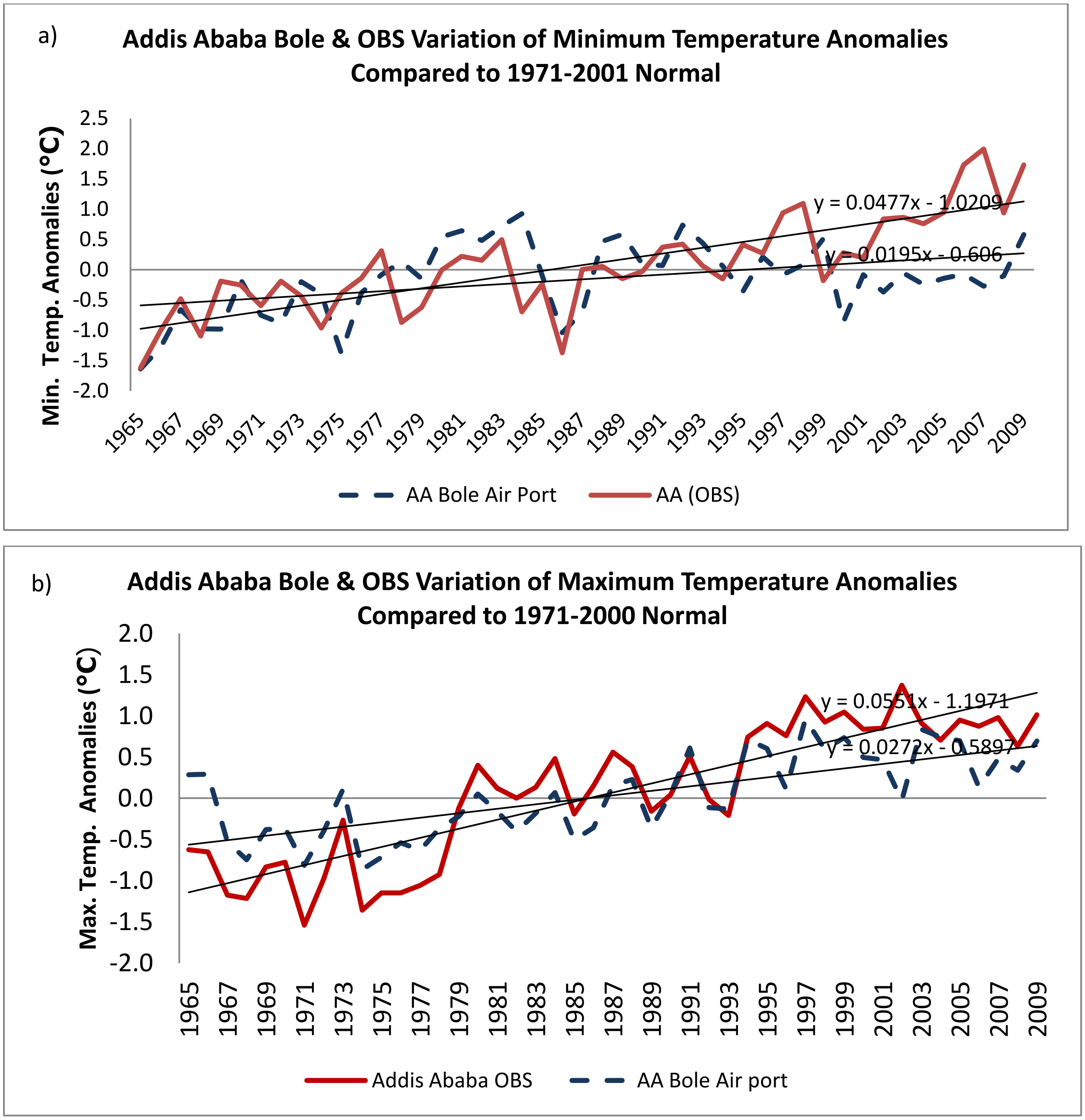


Figure4.1: Addis Ababa Bole Airport and Addis Ababa Observatory stations (a) Minimum and (b) Maximum temperature anomalies compared to the 1971-2000 mean.

Fig. 4.2 shows mean climatology of rainfall, maximum and minimum temperatures as revealed from observation at Addis Ababa observatory meteorological station and WorldClim data center for the 1950-2000 base line periods. The comparison shows near perfect agreements in all variables (minimum temperature, maximum temperature and rainfall).

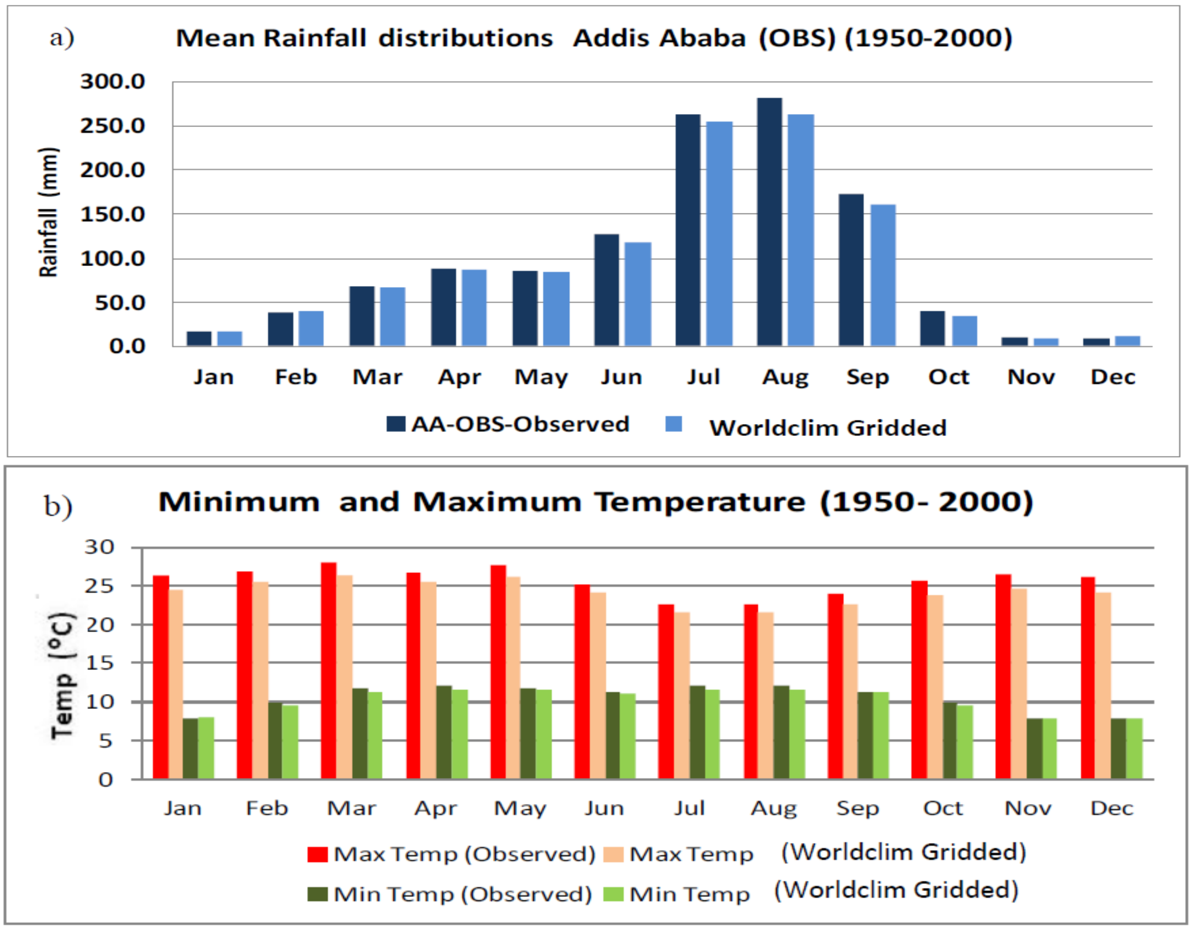


Figure4.2: The baseline means climatology: a) WorldClim and b) observation data for the baseline period 1950-2000 at the Addis Ababa Observatory station.

Fig.4.3 (a-c) shows mean rainfall, maximum and minimum temperatures as revealed from observation at Addis Ababa observatory metrological station and HadCM3 model data for the 1961-2000 baseline periods. The comparison of HadCM3 historic data, and observed Addis Ababa OBS data shows good agreements with rainfall, minimum, maximum temperature variables.

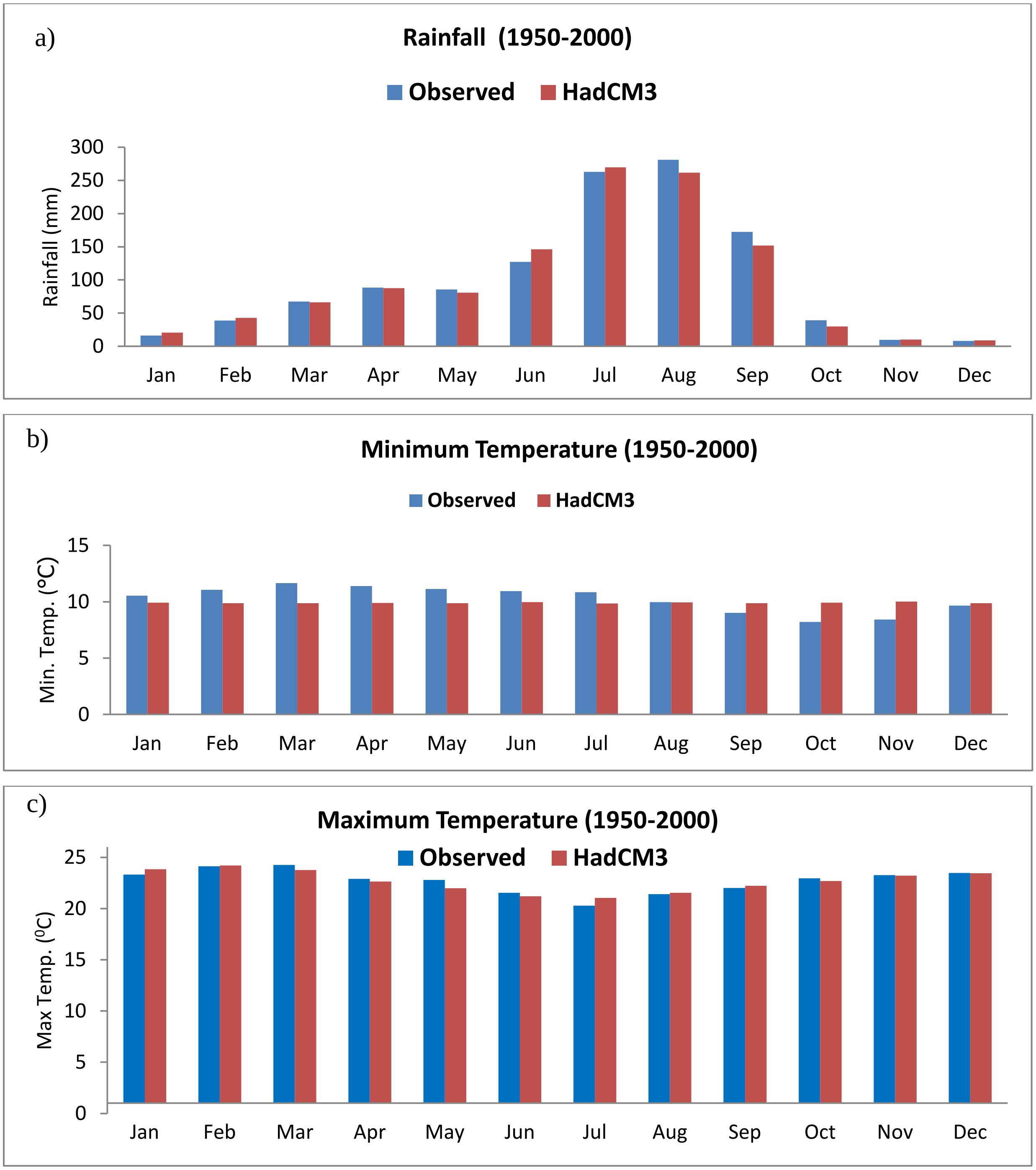
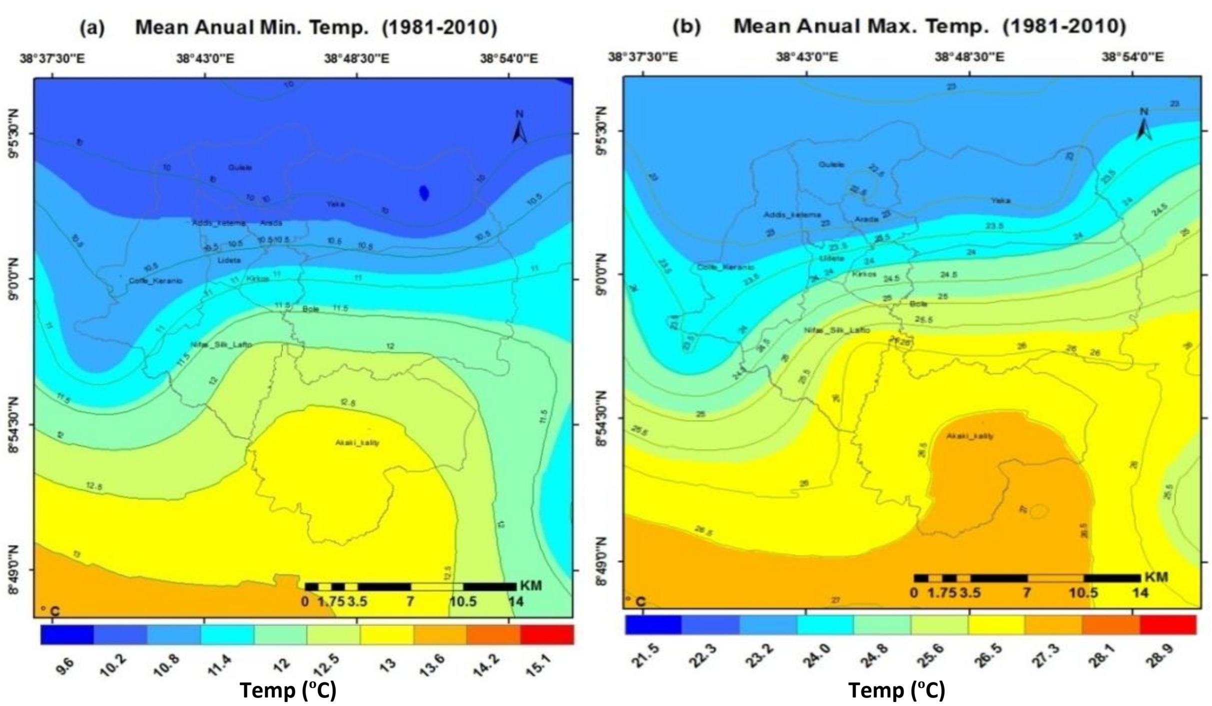


Figure 4.3: The mean climatology of Observed and HadCM3 model data for (1950-2000) a) Rainfall b) Minimum Temperature, and c) Maximum temperature for the Addis Ababa Observatory station.

The long term mean (1981-2010) of annual maximum and minimum temperature maps are reconstructed from gridded observation using Arc-Map 10.2 (Fig. 4.4a-b). Addis Ababa city is located in central part of Ethiopia and its topography is mountainous (as shown in Figure 3.1) and thus topographic feature modulates pressure, temperature, precipitation and wind patterns. As a result, over a relatively short distance from Entoto and Menagesha Suba mountains area in the north to Akakai Sub-city in the south, there are generally a decrease in rainfall with decreases in elevation (Figure 4.4c) and an increase in minimum temperature with decrease in elevation (Figure 4.4a). Likewise, maximum temperature follows similar patterns (Figure 4.4b).

The spatial pattern of mean annual minimum and maximum temperature shows decrease from Northern uplands of Gulele and Yeka sub-cities to Akaki-Kality sub-city (Fig.4.4a-b). The average minimum temperature of the city was between 10.3 ºC to 12.8 ºC, whilst the average maximum temperature was between 23.4 ºC to 28.6 ºC. The spatial distribution of annual total rainfall shows that Gulele sub-city in the north is the wettest (i.e. about 1160 mm), whereas Akaki-kality sub-city is the driest with mean rainfall of about 1010 mm (Fig 4.4c). The three climate variables seem to largely follow the elevation pattern (Fig. 4.4d). Generally patterns with high peaks enjoy cold and wet conditions, whereas low lying areas experience warm and relatively dry conditions.



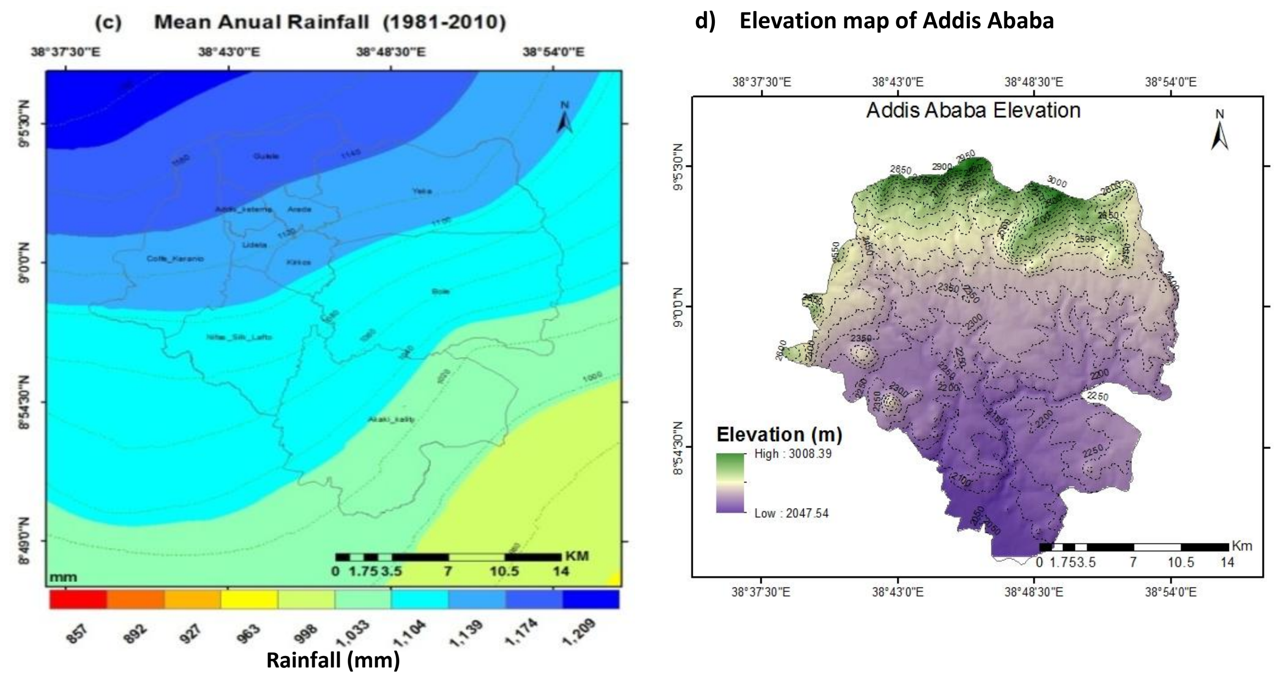
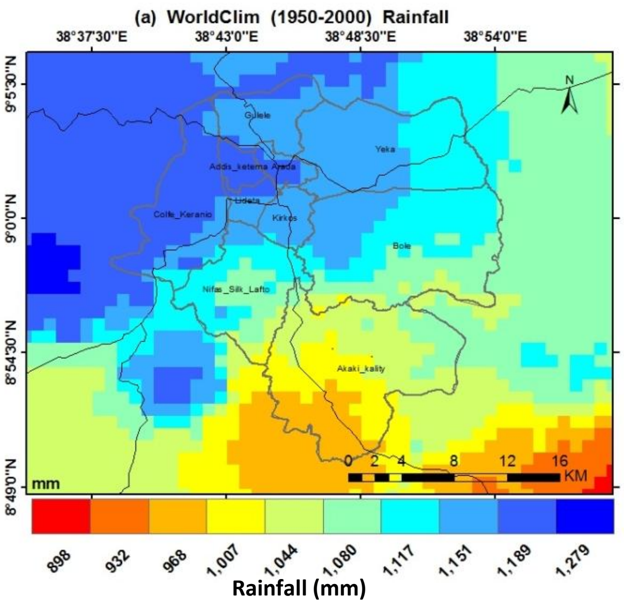


Figure4.4: Climate and topography of Addis Ababa: a) mean annual minimum temperature b) mean annual maximum temperature c) mean annual total rainfall for the period (1981-2010) and d) Elevation map of the city.

The comparison of gridded observation (Fig. 4.4), Worldclim and HadGEM2-AO (Fig. 4.5) shows strong agreements in spatial climate pattern of all variables (minimum, maximum temperature and rainfall). Rainfall decreases dramatically from the high-lying parts of the city in the northwest to the low lying Akaki-Kality sub-city in the south (Fig. 4.4c and 4.5a-b). The mean annual rainfall varies spatially from 950 to 1,158 mm per year across a distance of just 30 km. The seasonal distribution of rainfall at seven locations representing the sub-cities were the same except during summer (kiremt) during which August rainfall was high at the high-lying altitude of Kolfe-Keranio and Gefersain sub-cities in contrast to the low rainfall at the low-altitude lying areas of Legedadi and Akakisub-cities (Fig. 4.5g).


(a) WorldClim (1950-2000) Rainfall
38°37'30"E
38°43'0"E
38°48'30"E
38°54'0"E
9°5'30"N
9°0'0"N
8°54'30"N
8°49'0"N
Gulele
Yeka
Addis_ketema Arada
Lideta
Colfe_Keranio
Kirkos
Bole
Nifas_Silk_Lafto
Akaki_kality
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mm
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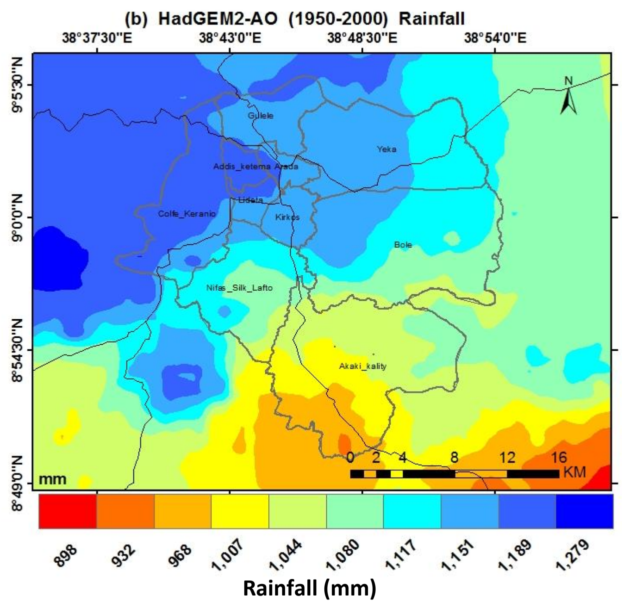
1,279
Rainfall (mm)


(b) HadGEM2-AO (1950-2000) Rainfall
38°37'30"E
38°43'0"E
38°48'30"E
38°54'0"E
9°5'30"N
9°0'0"N
8°54'30"N
8°49'0"N
Gulele
Yeka
Addis_ketema Arada
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Colfe_Keranio
Kirkos
Bole
Nifas_Silk_Lafto
Akaki_kality
0 2 4 8 12 16 KM
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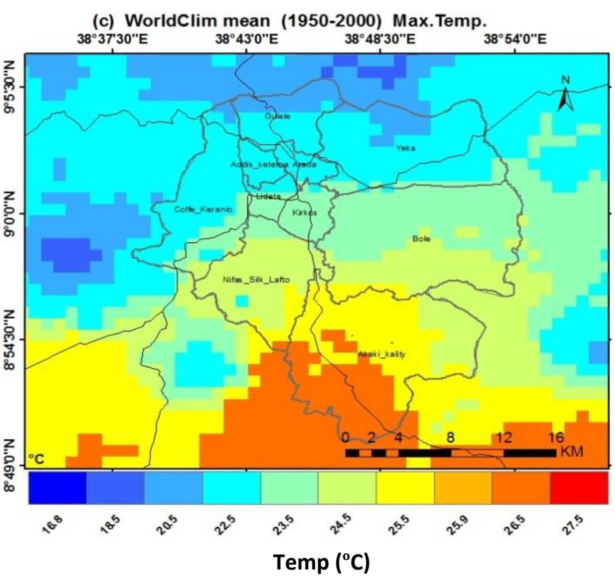
Rainfall (mm)


(c) WorldClim mean (1950-2000) Max.Temp.
38°37'30"E
38°43'0"E
38°48'30"E
38°54'0"E
9°5'30"N
9°0'0"N
8°54'30"N
8°49'0"N
Gulele
Yeka
Addis_ketema Arada
Lideta
Colfe_Keranio
Kirkos
Bole
Nifas_Silk_Lafto
Akaki_kality
0 2 4 8 12 16 KM
°C
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23.5
24.5
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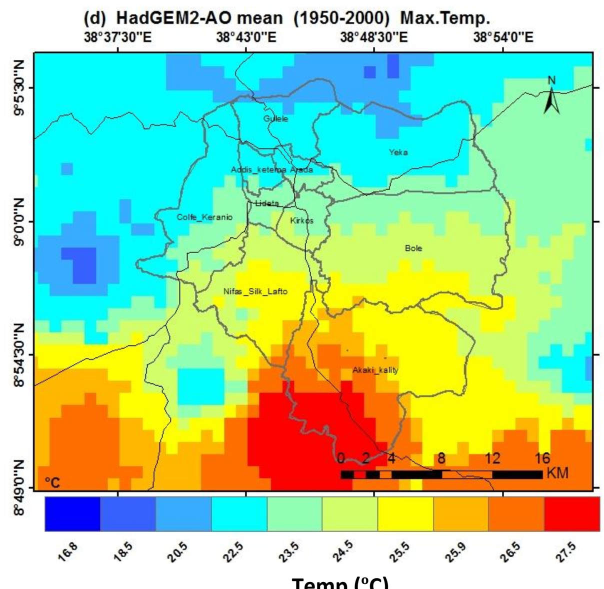
25.9
26.5
27.5
Temp (°C)


(d) HadGEM2-AO mean (1950-2000) Max.Temp.
38°37'30"E
38°43'0"E
38°48'30"E
38°54'0"E
9°5'30"N
9°0'0"N
8°54'30"N
8°49'0"N
Gulele
Yeka
Addis_ketema Arada
Lideta
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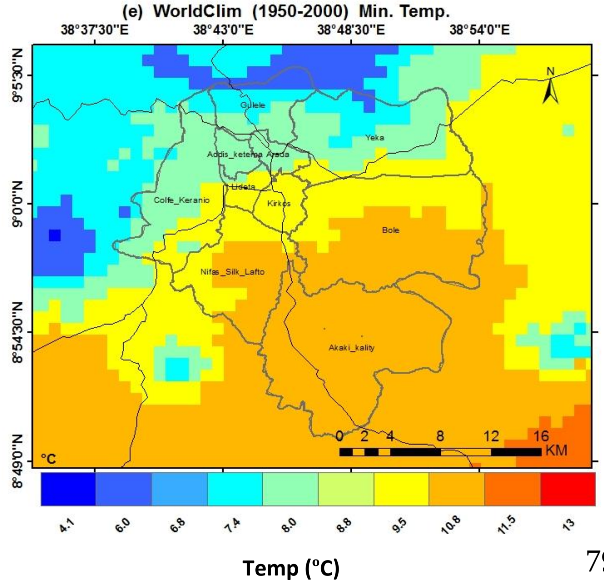
Temp (°C)


(e) WorldClim (1950-2000) Min. Temp.
38°37'30"E
38°43'0"E
38°48'30"E
38°54'0"E
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8°54'30"N
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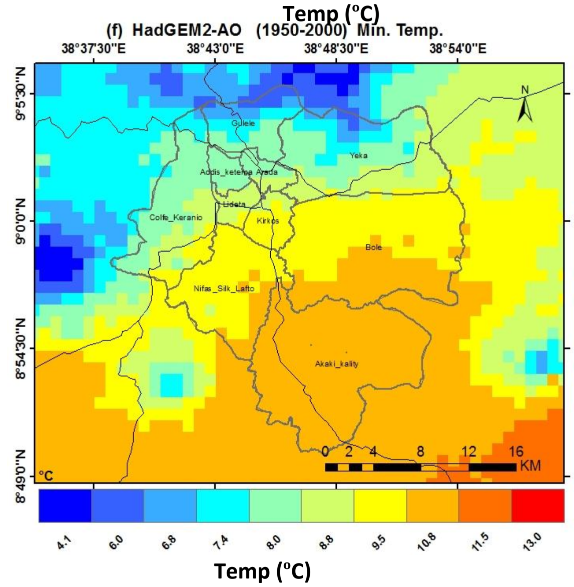
11.5
13
Temp (°C)


(f) HadGEM2-AO (1950-2000) Min. Temp.
38°37'30"E
38°43'0"E
38°48'30"E
38°54'0"E
9°5'30"N
9°0'0"N
8°54'30"N
8°49'0"N
Gulele
Yeka
Addis_ketema Arada
Lideta
Colfe_Keranio
Kirkos
Bole
Nifas_Silk_Lafto
Akaki_kality
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Temp (°C)

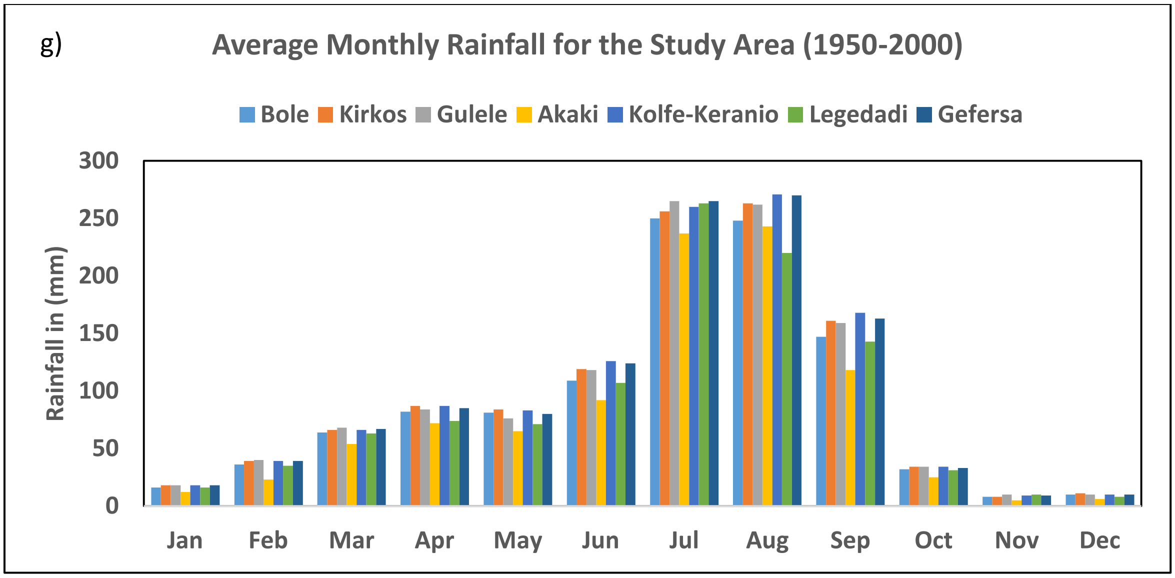


Figure4.5: The gridded observed WorldClim and HadGEM2-AO for mean 1950-2000: a-b) Annual Rainfall, c-d) Maximum Temperature, e-f) Minimum temperature and g) Seasonal distribution of rainfall at the location of seven sub-cities grid point of Addis Ababa and surrounding areas.

4.3.2 Signature of Climate Change for Addis Ababa under A2 and B2 emission scenarios

Fig. 4.6a shows the long term monthly mean minimum temperature for the 1950-2000 ranges from 8.2 to 11.4 at Addis Ababa Observatory. The minimum temperature anomalies during 2030s with respect the above baseline period will be -1.4 and -0.9 °C in December under A2 and B2 scenarios respectively. During 2050s, the mean monthly minimum temperature is expected to be warmer by 1.3 °C in November and 1.5 °C in December under A2 and B2 scenarios respectively. During 2080s, it is likely to be warmer by1.6 °C in November and 2.0 °C in December under A2 and B2 scenarios respectively (Fig. 4.6a). In general in both A2 and B2 scenarios an upward temperature trend is expected by the end of 21st century. The long term monthly mean maximum temperature for the 1961-2000 periods is in the range from 19.7 to 25.0 °C. The lowest maximum temperature observed in the month of July. The mean maximum temperature anomalies of urban center at Addis Ababa Observatory station during 2030s will increase by 0.6 and 1.2 °C in December under A2 and B2 scenarios respectively. During 2080s the mean monthly maximum temperature shows warmer anomalies of 2.4 °C in November and 2.1 °C in December under A2 and B2 scenarios respectively (see Fig. 4.6b).

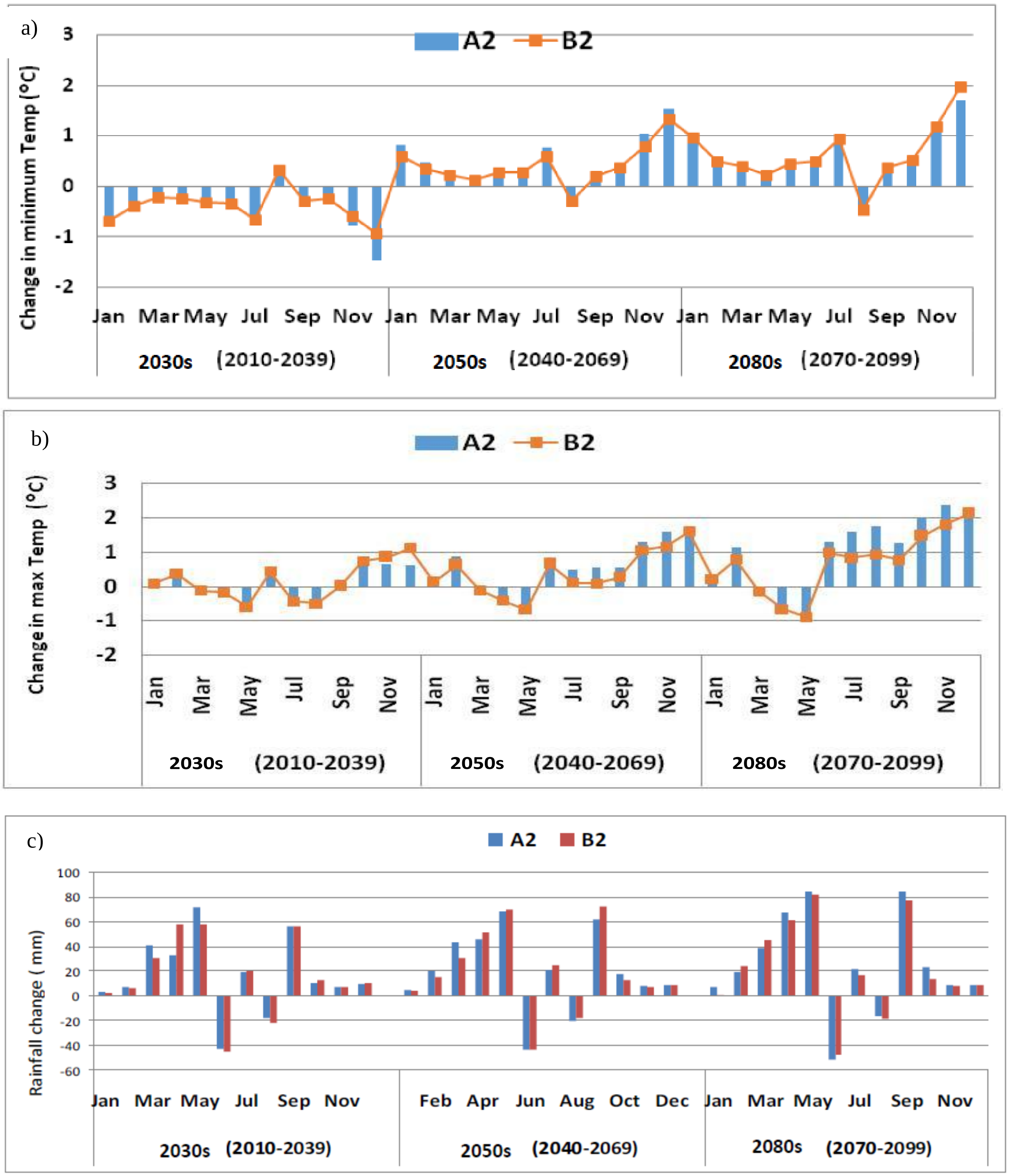


Figure4.6: Departure of down scaled: a) monthly minimum temperature b) maximum temperature and c) monthly average rainfall anomalies at Addis Ababa Observatory under A2 and B2 scenarios with respect to the 1950-2000 mean.

Change in precipitation shows increasing trends under B2 in March and decreasing trend in June to September during long rainy seasons in A2 and B2 in the 2030s period. B2 scenario shows the maximum precipitation during the month of September in the 2050s as compared to A2 scenario (Figure 4.6c). The A2 and B2 scenario noted an overall increase in rainfall, however a decreasing trend in the monthly precipitation particularly in major rainy season (e.g., June (43-45 mm) and August (22 mm)) during the 2030s and 2050s, and a decrease of up to 44 mm in June and 18 mm in August in 2080's while an upward trend in rainfall are expected in the month of September (up to 84 mm). Also in Belg or short rainy season, an upward trend is expected mainly in the month of April and May (up to 84 mm) during both the 2050s and 2080s periods (see Fig. 4.6c).

4.3.3 Projections under the RCP 4.5 and RCP 8.5 scenarios

The output from the National Institute of Meteorological Research (NIMR) with Met Office Hadley Centre using the Hadley Centre Global Environmental Model version-2 coupled with Atmosphere-Ocean configuration (HadGEM2-AO) include a bias-corrected midrange RCP4.5 scenario and RCP 8.5 high range emissions scenario (Baek *et al*., 2013; Im *et al*., 2015).
The data covers the period from January 1, 1950 to December 2099. The climatic baseline is chosen to cover the 1950-2000 period for evaluation of the projected changes in the mean annual and seasonal precipitation, maximum and minimum temperatures. A 50-year data set meets the IPCC requirements for a recommended baseline period (Parry *et al.*, 2007). The future periods assessed for the changes in climate under the RCP scenarios are 2030s (2010-2039), the 2050s (2040-2069), and the 2080s (2070- 2099) (Wayne, 2013).

The projected change in the mean monthly maximum temperature under RCP 4.5 and RCP 8.5 scenarios with respect to the baseline period mean is shown in Fig.4.7a-b. Projections under both scenarios indicate an increase in maximum temperature in each month for all three future periods. Compared to present-day conditions, strong maximum temperature change for all three projection periods (5.4 °C) appears in June under RCP 4.5, whereas under RCP 8.5, the maximum expected change will be 3.8 °C in June 2080's. Even though the observed maximum temperature is high in April and May for most parts of the city and surrounding areas, the temperature change for April and May is expected to be moderate. However, for June, the observed maximum temperature is low, but the expected temperature change is high in the 2080s under RCP 8.5 scenario.

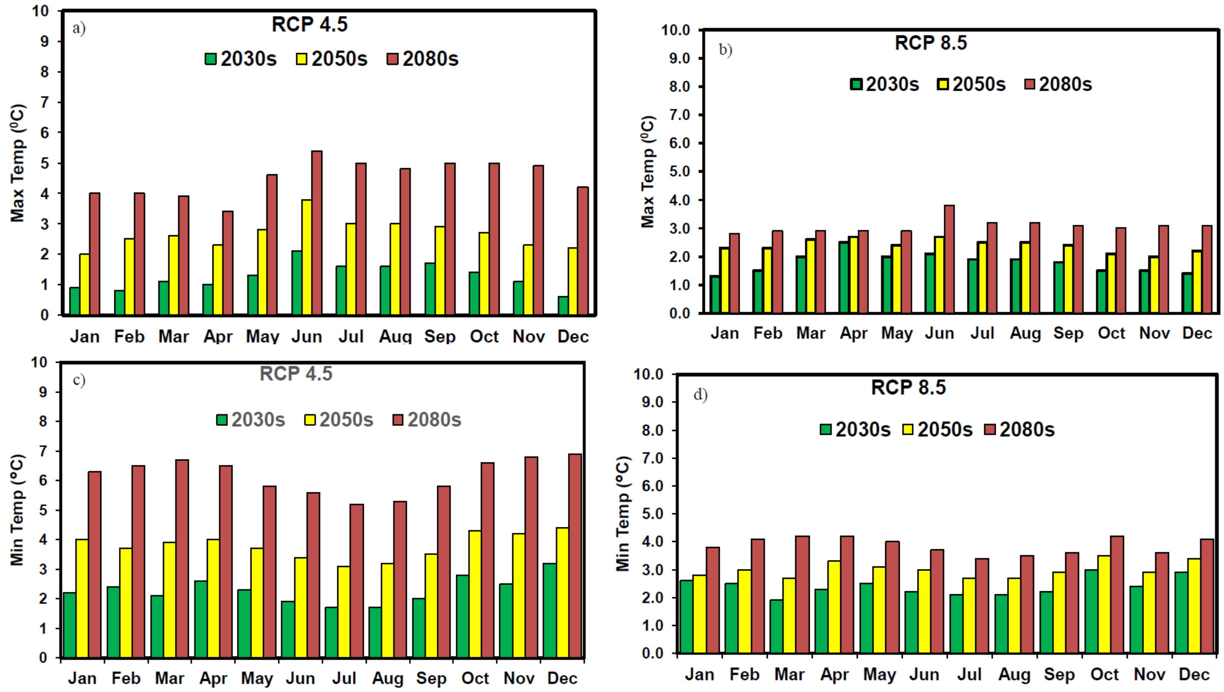


Figure 4.7: Projected future mean annual changes in (a-b) for RCP 4.5 and RCP 8.5 maximum and(c-d) for RCP 8.5 and RCP 4.5 minimum temperature in the 2030s 2050s, and 2080s with respect the baseline period (1950-2000) mean.

The mean monthly minimum temperature anomalies increase by 2.9 °C and 3.2 °C in December during the 2030s under RCP 4.5 and RCP 8.5 scenarios respectively. During 2050s the mean monthly minimum temperature anomalies increase by 3.4 and 4.4 °C in December under RCP 4.5 and RCP 8.5 scenarios in this order. During 2080s, the anomalies are expected to decrease by 4.1 and 6.9 °C in December under RCP 4.5 and RCP 8.5 scenarios respectively (Fig. 4.7c-d).

The box-plots (Fig.4.8) demonstrates that annual change of mean maximum and minimum temperatures of HadGEM2-AO during the 2030s, 2050s, and 2080s with respect to the baseline mean under both RCP 4.5 and RCP 8.5 scenarios. Both projections indicate increase in maximum and minimum temperature for all three future periods. It is also evident that (from the whisker box-plots) the range of change in annual temperature will increase with the time horizon. The middle 50 % range of the box represents the value of median. While the two ends of whiskers represent the extreme projections.

The changes in annual maximum and minimum temperature projections under RCP 4.5 are higher than RCP 8.5 in all periods with the exception of the 2030s maximum temperature. The median value of the maximum temperature in the 2030s, as projected under the RCP 4.5 scenario is 1.7 °C, which is higher than projected changes under RCP 8.5 scenario (Fig.4.8). The extreme lowest minimum temperature change in the 2030s as projected under RCP 8.5 is 0.6 °C, and in the 2080s the lowest change in minimum temperature is estimated to be about 5 °C.

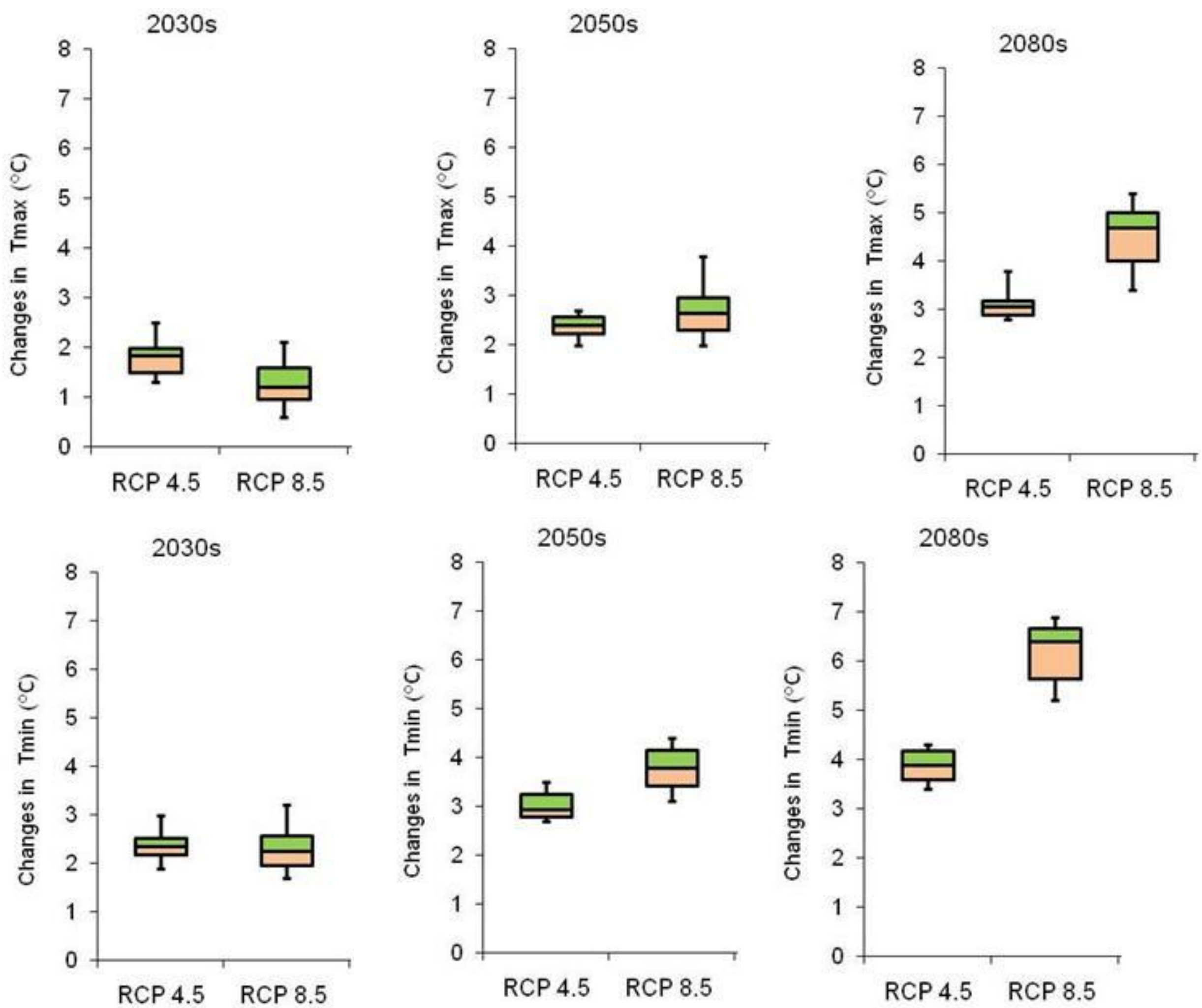


Figure 4. 8: Box plot for the mean annual changes in maximum and minimum temperature in the 2030s 2050s, and 2080s with respect the baseline period (1950-2000) mean.

The RCP 8.5 scenario shows an increase in future maximum temperature by about 1.0 - 2.5 °C for the entire city and surrounding areas through 2030s, with the highest change stretching along the Bole, Yeka, Lideta, and Akaki sub-cities in the eastern and southern parts of the city (see Fig.4.9-b as compared to Fig. 4.9a. By 2080s, average maximum temperatures are projected to increase by about 3 - 5 °C over the same areas. Fig.4.10 b-d shows the simulated mean minimum temperature during the 2030s, 2050s and 2080s.

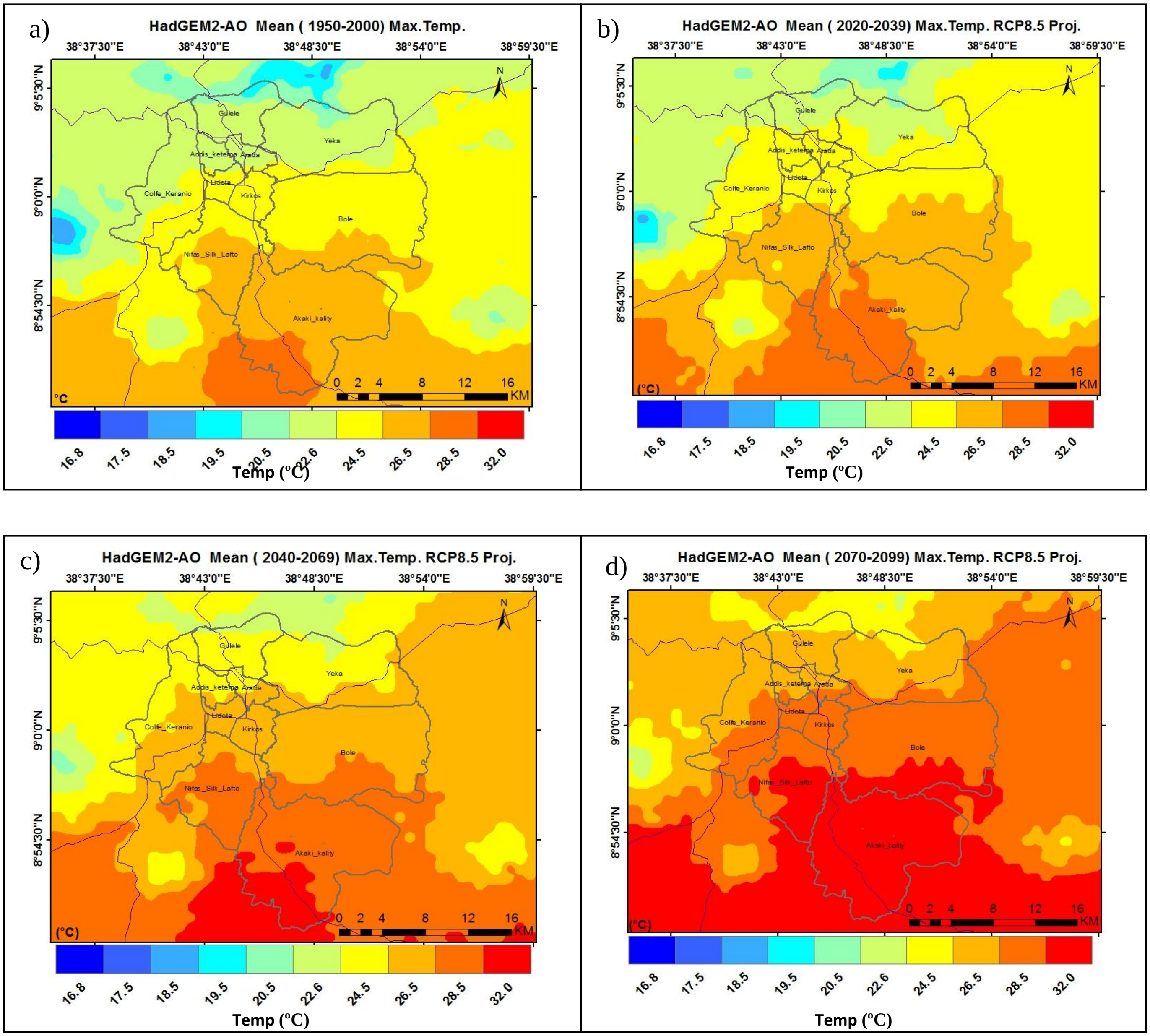


Figure 4.9: HadGEM-AO Maximum Temperature a) Baseline 1950-2000; b) RCP 8.5 2030s (2020-2039); c) RCP 8.5 2050s (2040-2069) and d) RCP 8.5 2080s (2070-2099)

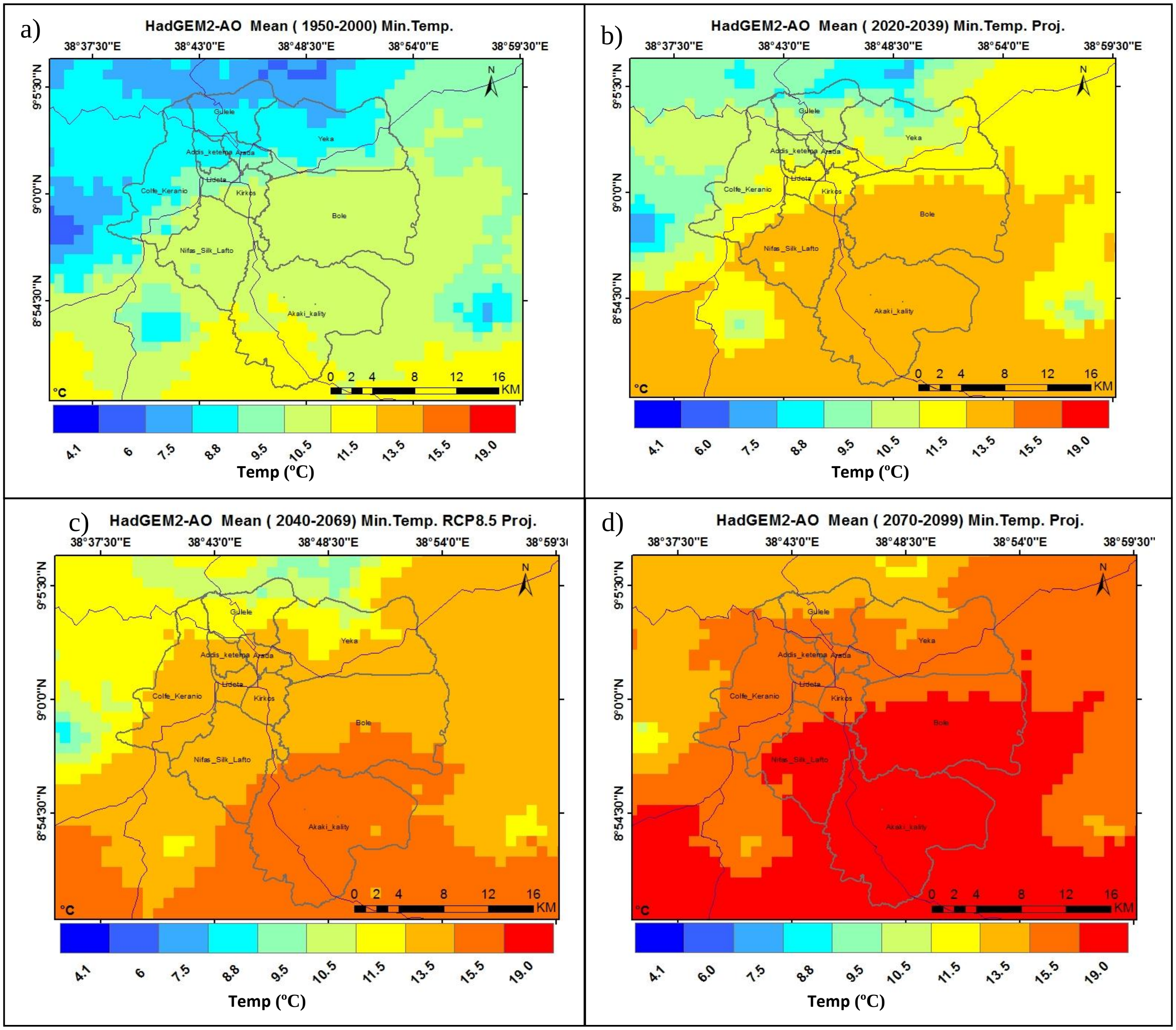


Figure 4.10: HadGEM-AO Minimum Temperature a) Baseline 1950-2000; b) RCP 8.5 2030s (2020-2039); c) RCP 8.5 2050s (2040-2069) and d) RCP 8.5 2080s (2070-2099).

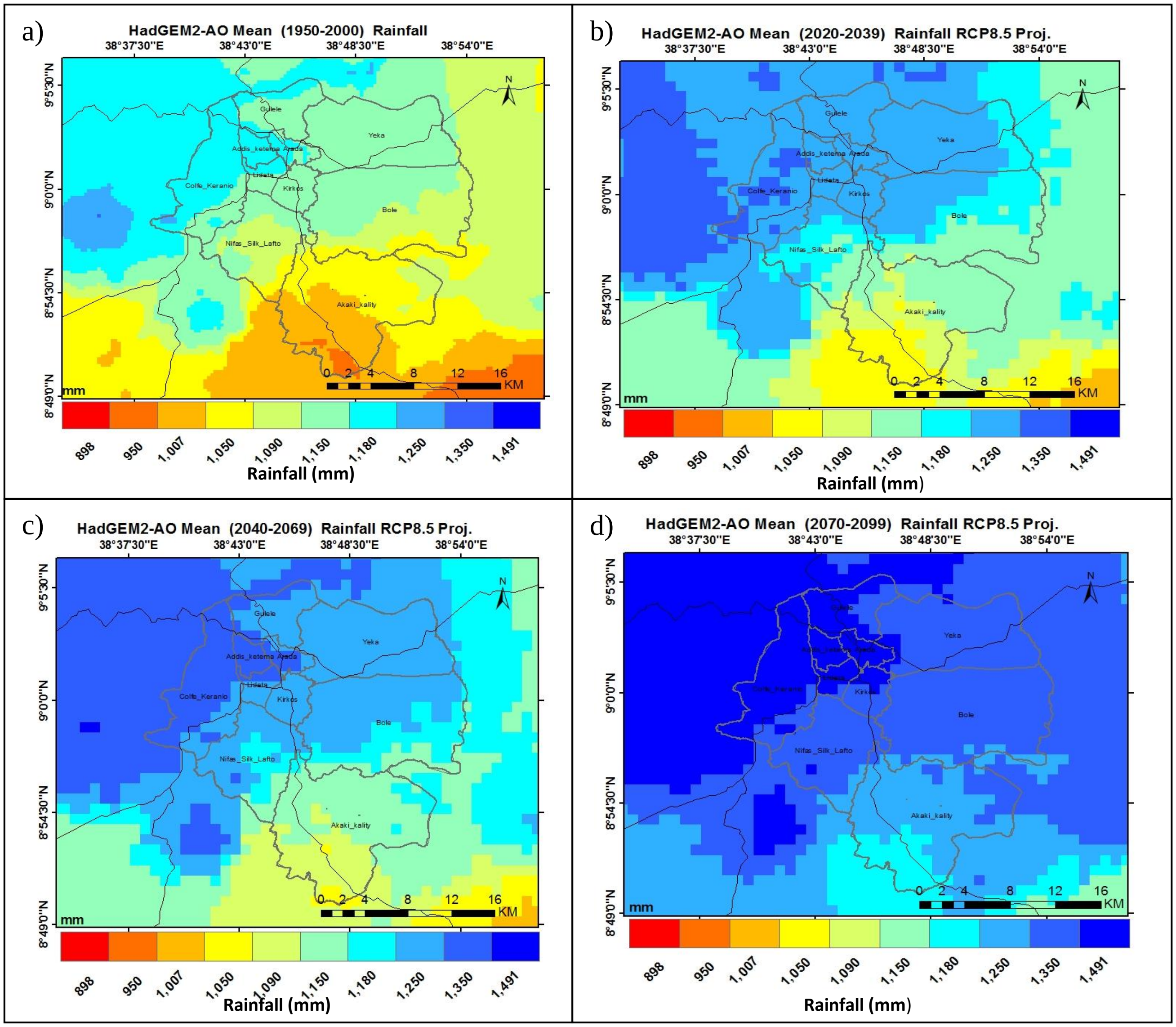


Figure 4.11: HadGEM-AO Rainfall a) Baseline1950-2000; b) RCP 8.5 2030s (2020-2039); c) RCP 8.5 2050s (2040-2069) and d) RCP 8.5 2080s (2070-2099).

The simulation under RCP 8.5 scenario shows increase in future minimum temperature for both time periods since there is a clear expansion from Akaki and Bole sub-cities towards Yeka and Gulele sub-cities (see Figure4.10b-d). These areas of the city are expected to experience the highest changes in minimum temperature in clear contrast to the maximum temperature change, suggesting that in the current estimation a minimum temperature is more sensitive to climate change. This is consistent with previous works in the literature (Lobell, *et al*, 2007).The rainfall projection under RCP 8.5 scenario shows that the simulated annual precipitation levels will increase from 1332 mm over mount Menagesha Suba during the 2030s to 1454 mm during the 2080s. Also in the low lying areas of Akaki Kalite sub-city, there will also be an increase from 912mm during the 2030s to 1044 mm during the 2080s (Fig.4.11a-d).

Fig. 4.12 shows rainfall anomalies over Addis Ababa for both the historical baseline (1950-2000) and projections (2006-2099) under RCP 4.5 and RCP 8.5. The wetting trend exhibited in the anomalies for the historical period is during the projection is expected to continue at an increased rate under both projections. The increase in rainfall is more pronounced under RCP 8.5 than RCP 4.5. However, there will also be dry periods of which 2042 will be the driest with a dry anomaly of up to 417 mm with respect to the baseline period (1950-2000) mean.

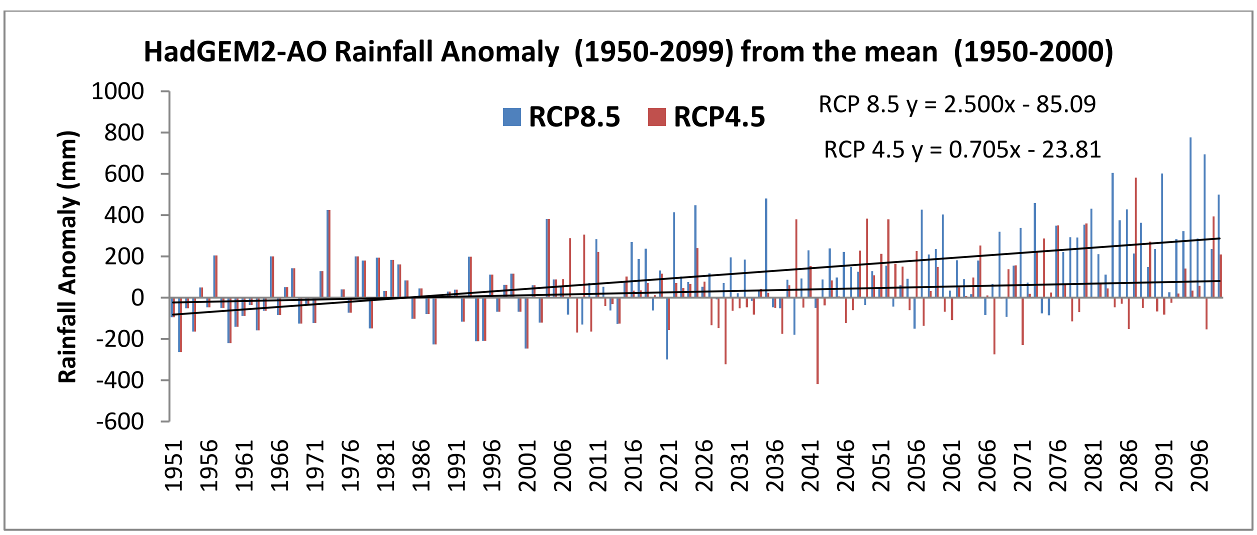
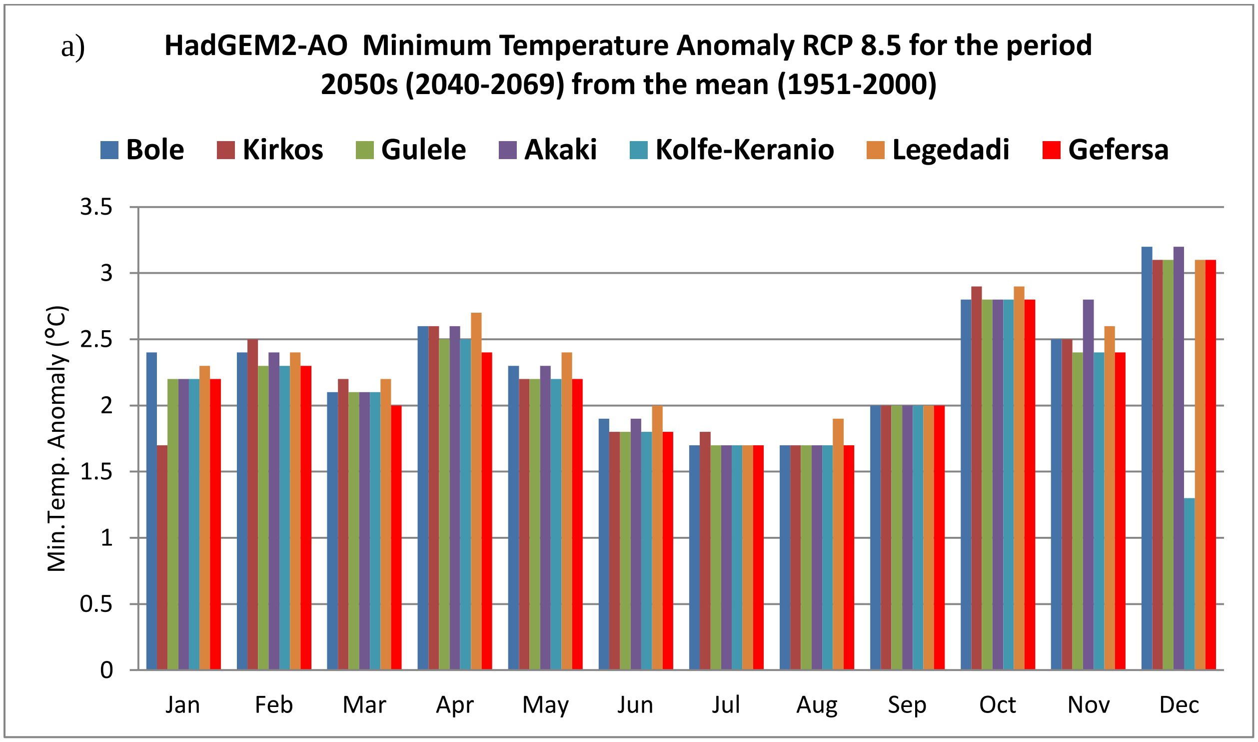


Figure 4.12: HadGEM2-AO projected Addis Ababa Observatory Station Rainfall Anomaly (2001-2099) from the mean (1950-2000).

Fig. 4.13a shows during 2050s (2040-2069) the mean monthly minimum temperature anomalies in sub-cities like Kolfe-Keranio and Akaki of Addis Ababa will increase by 2.8 and 3.2 °C in October and December respectively under RCP 8.5 scenarios. The Mean maximum temperature anomaly will increase by 4 °C in June under RCP 8.5 scenario (Fig. 4.13b).



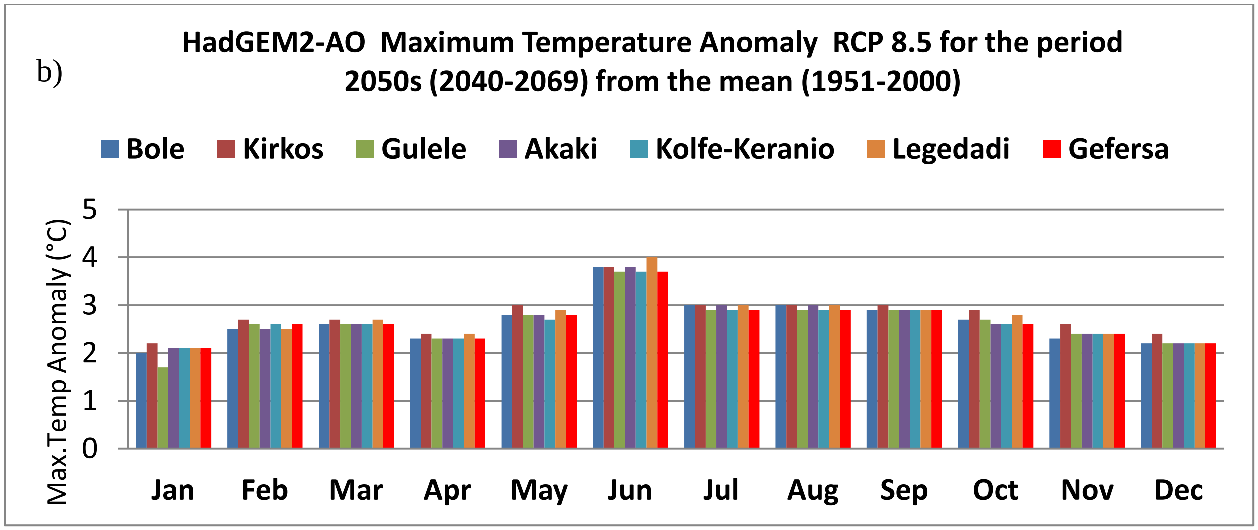
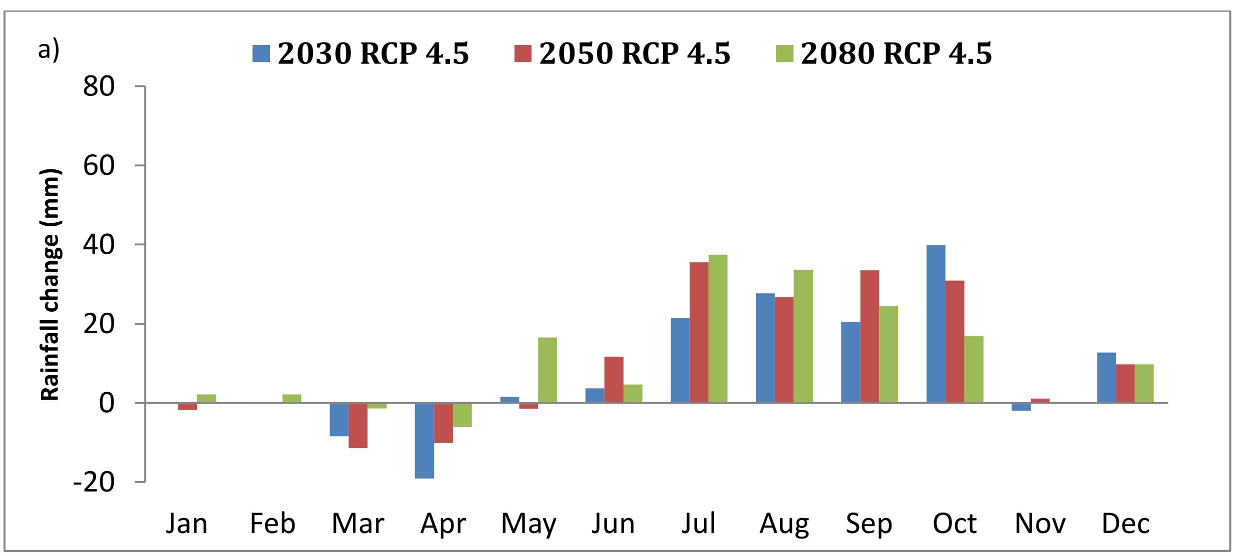
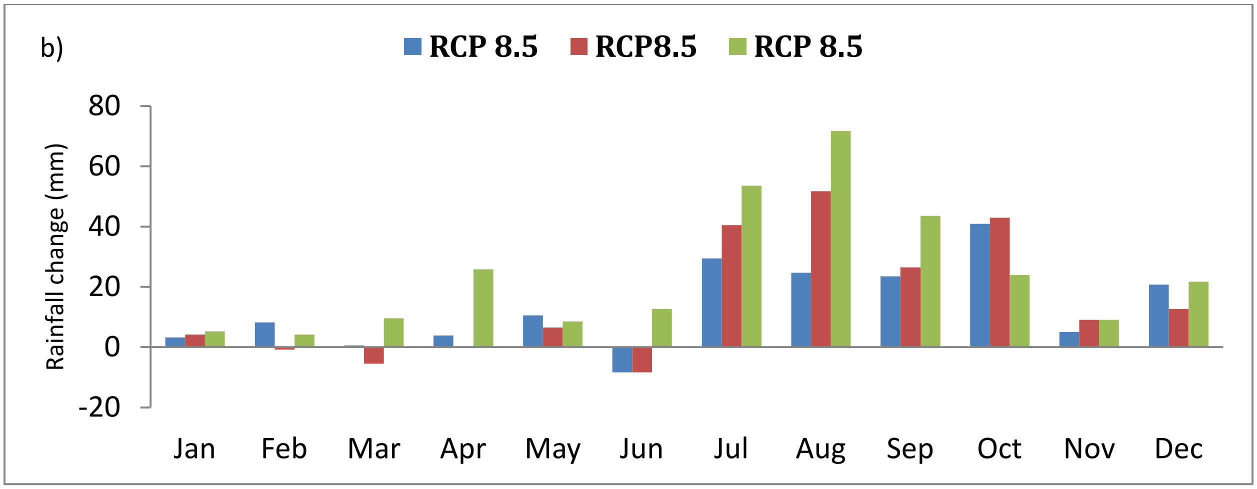


Figure 4.13: a) Mean monthly minimum and b) maximum temperature anomalies for the period (2040-2069) under RCP 8.5 with respect the baseline period (1951-2000) mean.

The Bega or dry season of the 2030s and 2050s is highly likely to witness an increase in rainfall of about 40 mm under both RCP 8.5 and RCP 4.5 scenarios (see Fig.4.14a-b). But the increase of precipitation during the 2030s and 2050s for short rainy season (FMAM) under both scenarios is relatively small. A greater increase in projected summer rain (JJAS) under RCP 4.5 is expected (Fig.4.14a) whereas during the 2080s under RCP 8.5 scenario, the projection shows a decrease of rainfall in September. In general, the future climate in the Addis Ababa and the surrounding areas is expected to be wetter (Fig.4.14c) under the two scenarios.

The upward trend in rainfall is likely to affect water catchment area positively. However, when the sub-cities are considered separately, there is a difference on the magnitude of changes indicating some sub-cities are likely to be affected more than others. For example, during long rainy season (JJAS), projection shows a range of possible outcomes from a 5 % decrease (e.g., Akaki, Lagadadi areas) in June to a 7 % increase (e.g., sub-cities to the north of the city centre) July-August period by mid-century. The risk of decreasing precipitation appears to be higher for the southern parts of the city. During the short rainy season (FMAM), the projection shows a decrease from 2 % to 4 % by 2050s (see Fig. 4.14c).





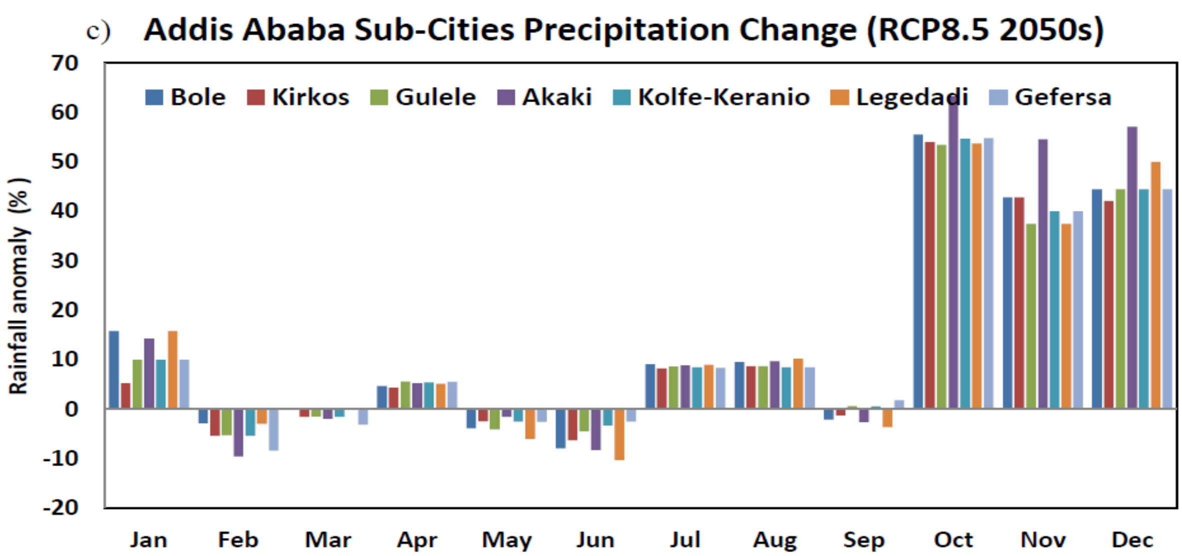


Figure 4.14: (a-b) Addis Ababa Observatory mean monthly change in rainfall in the 2030s, 2050s and 2080s under RCP 4.5 and RCP 8.5 scenarios with respect the baseline period (1950-2000) mean and (c) mean monthly percent of change in precipitation in the 2050s under RCP8.5 in sub-cities of Addis Ababa with respect the baseline period (1950-2000) mean.

Fig. 4.15 shows differences among the minimum, median, and maximum values of rainfall projections under RCP 4.5 and RCP 8.5 scenarios. The increase in median value of rainfall under RCP 8.5 is not high (about 4 mm) during the 2030s and about 14 mm in the 2080s compared with rainfall projections under RCP 4.5. The precipitation changes under RCP 8.5 are higher in the 2050s and 2080s compared with those changes under RCP 4.5.

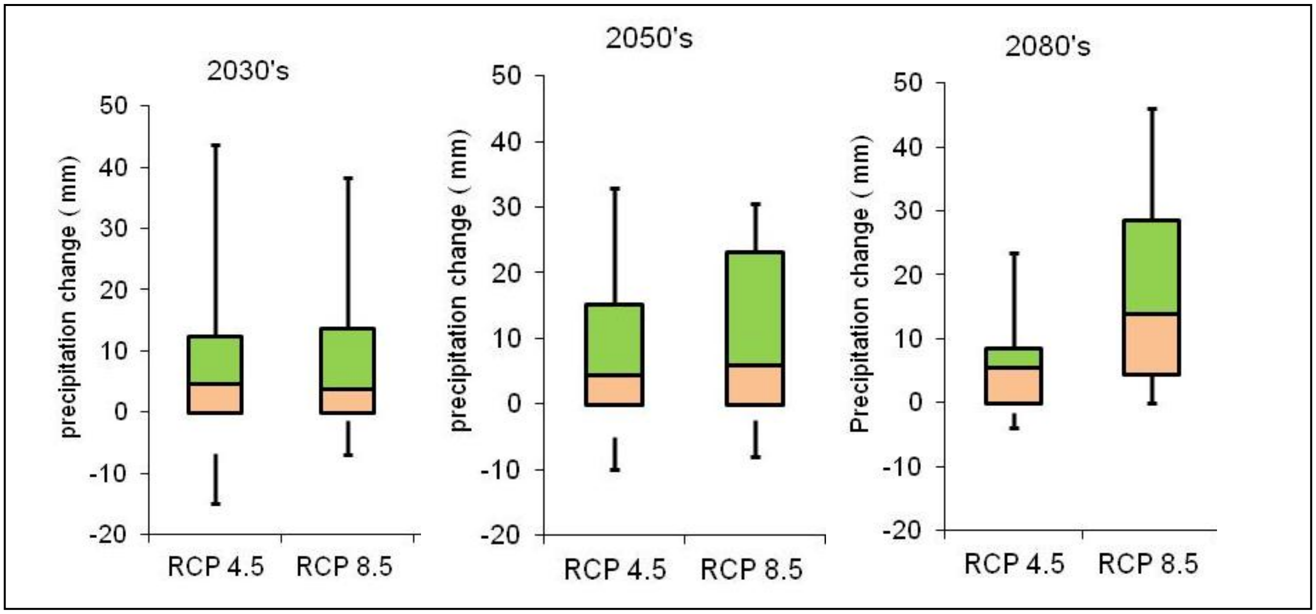


Figure 4.15: Box plot for the mean annual changes in rainfall in the 2030s, 2050s, and 2080s with respect the baseline period (1950-2000) mean.

4.3.4 Inter-comparisons of Climate Projection Scenarios

The projected mean monthly maximum temperature anomalies of A2 scenario shows an increase of 0.3 to 0.7 °C during 2030s dry season of November, 0.2 to 1.7 °C during 2050s and 0.3 to 2.4 °C from November to December in the 2080's. The B2 scenario also shows an increase by about 0.2 to 1.12 °C during 2030s, 0.6 to 1.6 °C during 2050s and 0.3 to 2.11 °C during 2080s. The projected monthly maximum temperature anomalies under RCP 8.5 scenario exhibited an increase of 1 to 2 °C during the 2030s dry season of November, 2.0 to 2.3 °C during the 2050s and 2.5 to 3.1 °C from November to December in the 2080s. The projection under RCP 4.5 scenario also shows increase by about 0.3 to 1.4 °C during the 2030s, 2.0 to 2.2 °C during the 2050s and 4.0 to 4.9 °C during the 2080s (Table 4.4). The projected maximum temperatures for the 2050s and 2080s under both RCPs scenarios are higher than those obtained under A2 and B2 scenarios.

Table 4.4: Inter-climate projections comparisons for selected months of the scenario periods.

Parameters	Projected periods	RCPs Scenarios		SRES scenarios		Remark
		RCP 4.5	RCP 8.5	A2	B2	
(August)Total monthly Rainfall change (mm)	2030s	0.0	-2	-17.9	-22.1	Change from observed mean of August rainfall, RCPs are higher than A2&B2 projections for 2050s and 2080s
	2050s	4.0	26	-20.7	-17.9	
	2080s	7.0	46	-16.3	-18.9	
(December)Min Temp change (°C)	2030s	3.2	2.9	-1.4	-0.9	Change from observed mean RCPs are higher than A2&B2 projections
	2050s	4.4	3.4	1.3	1.5	
	2080s	6.9	4.1	1.7	2.0	
(December) Max Temp change (°C)	2030s	0.6	1.4	0.6	1.1	Change from observed mean RCPs are slightly higher than A2&B2 projections
	2050s	2.2	2.2	1.7	1.6	
	2080s	4.2	3.2	2.1	2.1	

In Section 4.4.3, it has been shown that projected mean monthly minimum temperature anomalies under A2 and B2 scenarios will increase by 0.2 to 0.4 °C in August during the 2030s, by 0.4 to 1.5 °C in January and December during the 2050s and by 0.3 to 1.6 °C in November to December during the 2080s under the A2 scenario. On other hand projected change under RCP 8.5 indicates that minimum temperature anomalies shows an increasing trend of about 2.1 to 3.0 °C from August to January 2030s, 2.3 to 3.5 °C from January to December during the 2050s and 3.6 to 4.2 °C from November to December during the 2080s under the RCP 8.5 scenario. From the comparisons, we can conclude that the RCP 8.5 scenario tends to have higher values than those projected under A2 emission scenario.

The projected monthly rainfall change of A2 and B2 scenarios noted a decreasing trend in June (43-45 mm) and August (22 mm) during the2030s and 2050s, and up to a decrease of 44 mm in June and 18 mm in August in the 2080s while an increasing trend in rainfall in the month of September (up to 84 mm) is revealed. Also in short rainy season, an upward trend is expected mainly in the month of April and May (up to 84 mm) during both the 2050s and 2080s. On other hand the projected mean monthly rainfall changes under RCP 4.5 scenarios shows increase in June during the 2050s (about 12 mm). However, in April during the 2030s and May during the 2050s, rainfall shows a decrease by up to 10 to 15 mm. In Kiremt (JJAS), rainfall increases by up to 22 mm under RCP 4.5.The rainfall projections under A2 and B2 scenarios are higher than those under the RCPs.

4.4 Conclusion

The major objectives of this chapter are to assess and present the current change in climate for the city of Addis Ababa and to understand spatial variation of urban climate using HadGEM2-AO model output for present conditions and future climate under RCP 4.5 and RCP 8.5. Analysis of observations at the city center indicates existence of identifiable variability in rainfall and changes in temperature over time. The notable warm periods in the city of Addis Ababa in the 1990s and early 2000s, the dry periods of the 1970s and 1990s; as well as the above normal rainfall of 1982 and 1995are clearly evident from the anomalies with respect to the selected baseline period.

The mean climatology of simulated rainfall, maximum and minimum temperatures obtained from WorldClim data center are in good agreement with observed climatology at Addis Ababa Observatory for the same baseline period. The spatial variation in the mean climatology of the simulated variables is consistent with existing topographic features as revealed from observed distinct differences across north-south transect.

Four future scenarios are considered in this study to assess the climate variability and change at urban scale. Two scenarios from emission (A2 and B2) and two from representative concentration pathway (RCP 4.5 and RCP 8.5) scenarios are considered in this study. The change in rainfall, maximum and minimum temperature over Addis Ababa city and its surrounding is determined for three selected future periods with respect to the baseline period that extends from 1950-2000 under the four scenarios. The three future periods are categorized as the near term (2030s), mid-term (2050s) and end term (2080s).The observed major change in precipitation for all the three future terms for both A2 and B2 emission scenarios is of upward trend compared to the baseline period. The magnitude of the change between the two scenarios is different. This is also true across the seasons with higher rainfall under A2 than B2 during near and end terms. However, the rainfall under B2 is higher than A2 during mid-term. The maximum and minimum temperatures over Addis Ababa under A2 and B2 scenarios have shown warming future trend. However, if the three future periods are considered separately, both maximum and minimum temperature exhibit cooling trend with respect to baseline period. In contrast, the mid and end terms are expected to witness warming trends.

The rainfall anomalies over Addis Ababa from the baseline mean during future periods shows wetting trends generally under both representative concentration pathways. However, the rainfall anomalies are higher under RCP8.5 than RCP4.5 with significant difference during mid and end terms.

Downscaled HadGEM2-AO maximum and minimum temperature show warming trend over Addis Ababa city under both RCP 4.5 and RCP 8.5 scenarios. However, change in minimum temperature is higher than maximum temperature except under RCP 4.5 during the end term. The later is consistent with existing literature. Moreover, the change in minimum temperature is high under RCP 8.5 as compared to change under RCP 4.5. The overall average temperature is warmer under RCP 8.5 than under RCP 4.5. This is consistent with expected wetter condition under RCP 8.5 than under RCP 4.5. Though the basis for comparison of the old scenarios with the latest RCP scenarios is rather fluid because of different assumptions and the level of uncertainties involved, it has been found that the projected maximum and minimum temperatures for the 2050s and 2080s under both RCPs scenarios are higher than those obtained under A2 and B2 scenarios. However, the rainfall projections under older emission scenarios are higher than those under the RCPs.

Finally, this research chapter is important as it identifies urban scale spatial climate change assessment and prediction in the city of Addis Ababa for the first time. Currently, there is very little literature that makes reference to such findings under city conditions. This knowledge is crucial information that is useful to urban planners, urban infrastructure authorities and the scientists that are involved in application of urban climate modeling.

CHAPTER 5

IMPACT OF CLIMATE CHANGE AND URBANIZATION ON WATER SUPPLY AND DEMAND

5.1 Introduction

Studies indicate that extreme variability in water resources and significant decreases in stream-flow will be major threats across sub Saharan African countries in the coming decades (Rochdane *et al*., 2012). Water resources are among the most vulnerable as they are directly exposed to climate change (Raskin *et al*., 2009; Rochdane *et al*., 2012). This is important as one of the major limiting factors of economic growth is the relative availability of water (Yahaya *et al*., 2014). Recent research shows that climate change will increase the pace of the global hydrologic cycle with accompanied rise in temperature, variability and changes in precipitation patterns (Rochdane *et al*., 2012; Elala, 2011). Changes in the frequency and intensity of precipitation invariably affect stream flow and the resultant storage volumes of reservoirs. For example, such changes manifest themselves in the form of increased intensity of floods or occurrence of severe droughts which severely affect the water resources at local and regional levels (Bahri, 2012). Human induced climate change affects the quality and quantity of global water resources and this necessitates changes in the way these resources are managed (Aguilar-Manjarrez *et al.,* 2010). Sub-Saharan countries are among those most threatened by water stress, in view of the likelihood of extreme variability, seasonality, and decreasing stream-flows that are predicted to occur in the coming decades (Rochdane *et al*., 2012**)**. Drought in Sub-Saharan Africa is the dominant climate risk; it destroys the livelihoods of farming and pastoral communities and shatters their food security, whilst it also has a significant negative effect on GDP growth (UN-Water, 2012). On the other hand, floods impact on infrastructure, transportation, goods and service flows as well as clean water supplies and health negatively (Yahaya, *et al*., 2014; FDRE Climate Resilient, 2011).

Urbanization is a crucial element that impacts water resources in terms of both quantity and quality, at different spatial scales around the world (Zhou, 2014; Bell, 2015). Water resources are adversely impacted due to the increasing demands in population and urbanization (Roy *et al*., 2010). Sustainability in water resources refers to the maintenance of natural water resources in adequate amount and quality for human use and balanced ecosystems (Costa-Cabral *et al*., 2011). Ensuring adequate and sustainable supply of water and sanitation for sprawling cities is a major concern, particularly for developing countries, the achievement of which might be complicated due to temporal and spatial change of water supply and demand (UN-Habitat, 2010). Data on the worldwide use of water indicates that the total abstraction for urban use is very low. Similar trend exists with respect to access to improved sanitation (WWAP, 2009). A study conducted on selected Chinese cities has concluded that a significant reduction in water table and degradation of water quality had resulted from the excessive use of ground water resources (Stephen *et al*., 1998).

As this is linked with increasing level and high rate of urbanization, this can also be taken to happen in other developing countries. There is a need to make concerted efforts towards effective management of water resources in sub Saharan Africa, which has a very low coverage of both potable water and improved sanitation, and which currently lacks the economic, human and institutional capacities to manage water resources on a sustainable basis (UN-Water, 2012).

Moreover, due to high population growth water supply pressure is increasing in Africa. Even though water resources are plentiful in some regions, water shortage has been a major restriction to the economic development in other regions (Brown and Hansen, 2008; IPCC, 2007). Countries should thus take into account in their national plans the need to ensure reliable water supply and hence the ever-increasing demand for water as well as the financial and physical resources that would be required to establish water supply systems. Also countries should take defensive approaches in addressing insecurity in water supply. The demand for water tends to increase with higher levels of development as the intensity of water use would increase to enable as well as sustain economic growth. Studying the water resource management concept is crucial in expanding urban development environments (WHO/UNICF, 2012).

The urbanization rate in Sub-Saharan Africa is increasing (George, *et a*l., 2011). Addis Ababa is one of these fast growing sub-mega cities in recent times (AACPPO, 2014). As the administrative seat and political capital of Ethiopia, the city attracts the highest number of migrants from other parts of the country (ORAAMP, 2002). As the supply of water must be assured for all, to meet the basic human needs, there is a need for progressive water supply planning and management system for the city in order to bring about fundamental changes in the ways water is currently used as well as distributed among different categories of users (AAWSA, 2012). The importance of demand-side management, in particular, is vital in view of the fact that the supply of water cannot be simply increased indefinitely to meet the otherwise increasing demands from the household, commercial, construction, industry and other sectors as well as the needs of the ecological reserves (Mulwafu *et al*., 2003; Buytaert *et al*., 2012).

Growth in population and economic activities as well as improvements in living standards of the population would entail increasing demand for water. In case of Addis Ababa, which is evolving into a mega-city, the construction boom including the expansion of condominiums and real estate housing developments, the expansion of manufacturing and service sector establishments that has occurred during the last decade, and the significant increase in its population that is expected to occur in the coming years presupposes a sustainable water supply planning and management (AACPPO, 2014). As water resources are susceptible not only to these pressures but also to impacts of climate change; environmental managers, urban planners and policy makers need to find solutions for climate change and urban development impact and alternative water sources for the existing and future pressures (Eriyagama *et al*., 2010; Yahaya *et al*., 2014).

Given the relationship between urbanization and water on the one hand and between climate change and water on the other, the goal of this work is therefore to investigate the potential impact of climate change on urban water supply by taking the City of Addis Ababa as geographic study area.

The aim of this chapter is to investigate water demand and supply prospects for the City of Addis Ababa by applying the WEAP hydrological model and using scenarios of population growth trends and climate change.

Specific Objectives are:

- To assess the current situation regarding the supply and demand for water in the city of Addis Ababa;

- To predict the water supply and water demand balance for the city in relation to plausible scenarios with regards to future population growth and climate change.
- To propose workable adaptation strategies that will contribute towards overcoming the negative impacts of climate change on water supply in the city.

This chapter is organized such that Section 5.2 describes the data and methods employed in the study. Section 5.3 presents the results and discusses trends in water consumption and the water supply system in Addis Ababa. This section incorporates projections of water supply and demand under assumed climate scenarios. Moreover, the impact of population growth is one of the considerations for the analysis of the water supply, demand and management system. Recommendations on management options for the un-met demands for each site are also outlined in this section of the chapter. Finally, the conclusion is given in Section 5.4.

5.2 Data and Methods

5.2.1 Data

Observed domestic and non-domestic water demand data obtained from AAWSA (2012), whereby information on the aggregate amount of water consumption for the year 2012 as indicated on the water bills of households at eight demand sites or branches of the city are used. The most important sources of water are surface and ground water systems (MESP, 2011). The main water supply elements are Legedadi, Dire and Gefersa reservoirs as well as the Akaki ground water reservoirs (Fig. 5.1). Daily and monthly data from Legedadi and Gefersa rainfall stations and the evaporation pans record of Legedadi and Gefersa for the year 2012 are used. Also the monthly inflow, storage capacity, and evaporation data for the year 2012 were collected from AAWSA. The preferred modality of water supply is when a given demand site is connected to more than one supply source. Water supply data for 3 reservoirs, 63 wells and 5 springs for the year 2012 were collected from Addis Ababa Water and Sewerage Authority (AAWSA).

Table 5.1: The total water supply data inputs volume of the reservoirs for the year 2012 (data source AAWSA, 2012).

Water Supply System	Sub-system	Input Volume in (m^3) for 2012
System I (Legedad and Dire) Reservoirs	Gabriel-Saris, Jan-meda, Teferi-Mekonin, Interconnection of Merkato, Entoto / Ras-Kasa and Belay Zeleke	59,425,092
System II: Gefersa Reservoir	Rufael, Core-Kolfe and St. Paul	11,306,884
System III: Akaki groundwater aquifer and other Ground water aquifer (63 wells and 5 Springs)	Akaki, Sarries and Legedadi west	41,442,775
Total		**112,174,751**

5.2.2 Methods

5.2.2.1 Water Evaluation and Planning (WEAP) model

The WEAP model is used for this study. WEAP is specifically effective as a proactive management tool, while it effectively simulates water demand, supply, flow and storage. The WEAP model is being applied at national and international levels as it provides a flexible and comprehensive framework for policy analysis as well as a system for maintaining water supply and demand information (SEI, 2007).

WEAP is capable to simulate suitably for the supply of and demand for water as well as the pressure on and utilization of surface and groundwater sources. WEAP can be employed in water assessments to be conducted at various spatial levels and temporal horizons. The WEAP program developers provide technical assistance and the method is in the public domain for academic use (SEI, 2007).

5.2.2.2 Water Supply

Using the WEAP model the various water supply sources are connected to each demand site by creating a transmission link from the various supply nodes to the various demand sites in order to satisfy the aggregate demand at each demand site (MESP, 2009). The total amount of water to be delivered to the demand site equals the amount to be withdrawn from the source minus the potential amount of losses. However, data on the water loss for each demand site is not available at AAWSA. These links are also used to "transmit" from demand sites to destinations such as treatment plants or receiving water bodies (MEPS, 2011).Hydrological data that include monthly inflow, storage capacity and net evaporation were collected form AAWSA. Projected future precipitation described in Chapter 4 is used. The climate model outputs of NIMR-HadGM2-AO model data for RCP 4.5 and RCP 8.5 scenarios (obtained from Mengistu Tsidu, 2016 unpublished work) and the mean precipitation for reservoirs' respective catchment areas for the period 2013 to 2039 were used to make assessments on the impacts of climate change on water supply- demand balance in WEAP. There has been an increase in the reservoirs storage capacity and number wells in the year 2012 as compared to the situation in 2005, due to upgrading of reservoir capacity and construction of new wells. The year 2012 water supply data presented in Table 5.2 was used in this study.

Table 5.2: Reservoirs storage capacity: (data source, AAWSA, 2012).

Reservoir	Storage capacity in MCM (2005)	Storage capacity in MCM (2012)
Legedadi and Dire	57.8	60.2
Gefersa	8.3	11.3
Akaki well, City springs and deep weels	14.6	33.6
Total	80.7	105.1

5.2.2.3 Water demand

Fig. 5.1 shows the schematic presentation of water demand sites or branches and supply for Addis Ababa. The courses of the main rivers are shown in blue lines, whilst the reservoirs are indicated with green triangle symbols. Ground water supply from wells and springs is indicated using green square symbol. The transmission links (in green lines) and the return flows (in red lines) are marked with arrows to show the flow directions. The main demand nodes considered in the model (red points) are for domestic and non-domestic distribution centers: For this study, the eight customer distribution centers or branches in the city are identified as demand nodes. The distribution centers include Arada, Mekanissa, Gulele, Addis Ketema, Megenagna, Akaki, Gurd

Shola and Nefassilk. When a demand point is created, it is important to indicate the level of priority given to it for allocation of water (MESP, 2011). The model will attempt to supply the highest demand priority first, and then move to lower priority points until all the points are covered. For the baseline scenario, the demand priority setup is water supply and flow requirements for domestic (households) and non-domestic (industry, commerce and construction) use. Each demand site is connected with a supply source using a Transmission Link (green line in Fig.5.1). Portion of the already used water flows back into the river systems (Return Flow - red line in Fig. 5.1). To determine the water demand for each demand node indicated in Fig. 5.1, data on yearly demand and monthly variation will be employed in WEAP model.

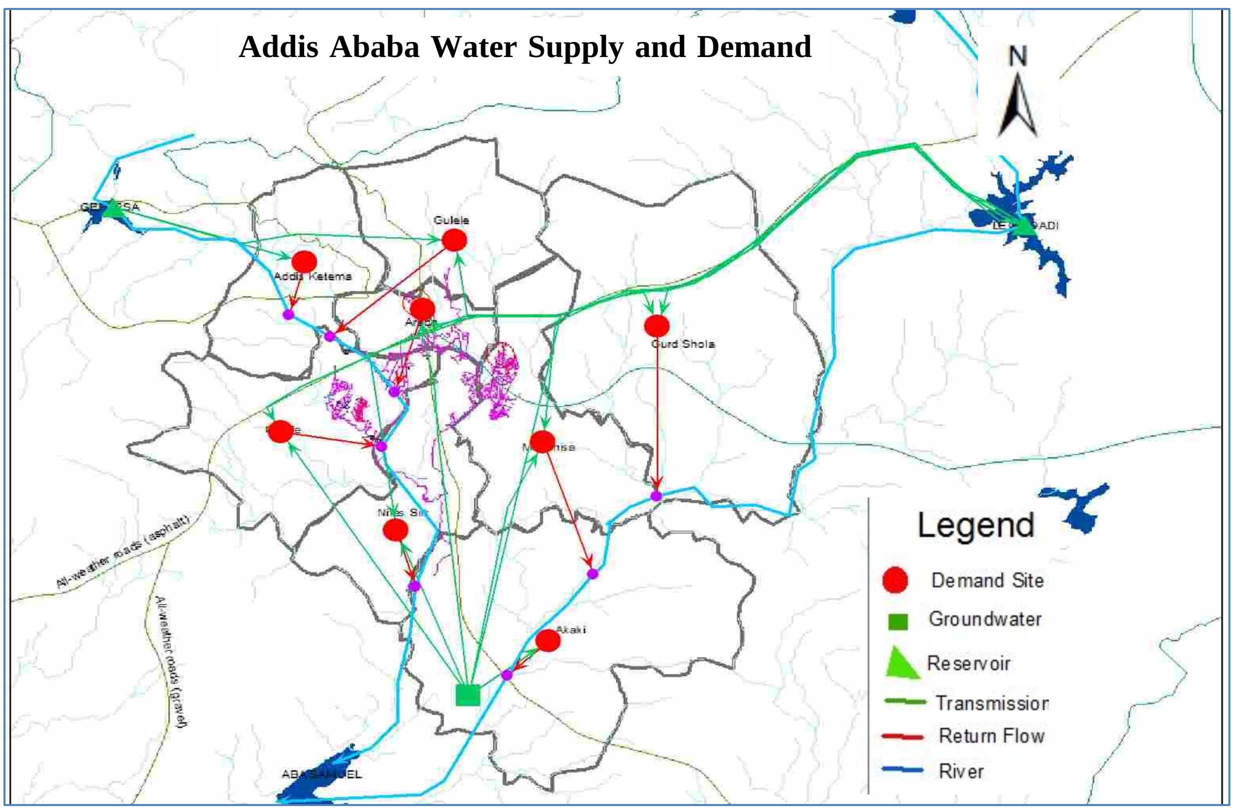


Figure 5.1: The schematic views of water demand branches and supply areas in the city of Addis Ababa.

The demand for water is calculated as follows:

$$Total\ demand = Total\ activity\ level\ \times Water\ use\ rate \qquad \text{Eq. (5.1)}$$

Using WEAP, demand for water is analyzed as the sum of the demands of demand sites (DS) for all the demand site's bottom-level branches (Br):

$$DemandAnnual_{DS} = \sum_{Br}(TotalActivityLevel_{Br'} \times Wateruserate_{Br''} \times \dots)$$

Eq. (5.2)

Bottom-level branch is the total activity level for the product of the activity levels for all branches from the bottom branch back up to the demand site branch (where Br is the bottom-level branch, Br' is the parent of Br, Br" is the grandparent of Br, etc.) (SEI, 2014).

5.2.2.4 Key Assumptions

The key assumptions refer to user-defined variables that can be referenced for the analysis of the water supply and demand systems (Leevite, *et al*., 2003). The key assumption was made mainly because of difficulty to obtain data. Both population growth and climate change have an impact on water demand and supply. It is also important to ensure that the units (for example m^3 per month verses m^3 per year, etc.) of the parameter value for key assumptions match the units for variables in the WEAP data tree (MESP, 2011). The key assumptions about water demand, water supply and water management are given in Table 5.3. The following demand and supply management options are considered in the key assumptions:

- **The World Bank calculated the Ethiopian gross domestic product** (GDP) 8.0 % in 2010 and 7.0 % in 2012. Projected Per capita GDP is expected to grow at around 8.5 % annually between 2013 and 2030 (FDRE, 2011). This will contribute to the growth of Addis Ababa and increase the average amount of water consumption in the city.
- **Price of water** (water tariff) from AAWSA (2012): the average tariff (price / m^3) for customers in the lowest consumption users in Addis Ababa is Birr 2.60 /m^3 or 0.12 USD per m^3 in 2012 (at the average exchange rate for 2012). The unit price of water in Addis Ababa has shown a slight change in the last 6 years. For this study it is assumed the unit price has increased and will reach Birr 4.40 / m^3 by 2039.

- **Technology innovation:** it is assumed that water leakage and other factors that contribute to water losses will be reduced from the current 39.85 % to 10 % by 2039 (AAWSA, 2012).
- **Water use efficiency (**leakage improvement and other growth of technology for efficiently water supply) is improved by 2 % for the reference year (2012); and annual improvement in efficiency expected to increase by 5 % until 2039 (AAWSA, 2012).

In case of supply management, according to AAWSA business plan (2012), there will be addition of new reservoir dam, Gerbi (29.2 million m^3 by the year 2016), upgrading of Legedadi which will add 11 million m^3 by 2014 and new wells which will start to supply about 90.1 million $m^3$of additional water over the period from 2014 up to 2020. This addition (a total of 130.3 million m^3) will be taken into consideration in management options as one of the supply measures. The second option incorporated was the potential impact of decreasing the water leakage from 34.3 % to 10 % that will contribute to efforts aimed to cater for the unmet water demand. Dry and wet seasons of a given year influence the rate of water consumption by the population. This is in fact the case as shown in Table 5.4. The level of consumption is expected to increase during dry climate years sequence. Table 5.3 shows the value of water consumption in different climate scenario.

The size of the population is expected to increase and the per capita water consumption is supposed to increase from the current level of 110 l/c/day in 2012 to the standard recommended by the World Health Organization (WHO) during the period considered by the present study. The current level of consumption is already below the WHO standard of 135 l/d, which is expected to increase up to 150 litter per day during dry seasons (Rochdane, *et al*., 2012) (Table 5.3).The key assumptions about domestic and non-domestic water supply, demand and management are outlined in Table 5.3.

Table 5.3: Key Assumptions for water demand and supply system and Model inputs for the Management options.

Key Assumptions	**Base period (2012)**	**Scenario period (2013-2039)**	**Unit**
Population growth	2.1	2.5 and 3.3	Percent / year
*Annual water use	37.9	65.5	m^3
GDPgrowth of Ethiopia for living standard	7.0	GDP Growth by 8.5 %	Percent / year
Management Options			
Price of water average of domestic and non-domestic	2.60	Growth by 2 %	ETH birr / year
** Water users Technology Innovation (water use method)	2	5	Percent / year
*** Water supply Efficiency annual improvement (leakage control)	39.85	10	Percent / year

* Total water use / person / year; ** driver to improve of water use technology for domestic and non-domestic customers (e.g. water taps, toilet flush); *** leakage improvement and other growth of technology for efficiently supply water by water suppliers.

Table 5.4: Assumptions of water consumption in different climate scenarios at low population growth.

Climate Condition	Water consumptions (litter/day)	Rainfall conditions
Normal climate	135	Normal
RCP4.5	135	Dry
RCP8.5	150	Relatively Wet

5.2.2.5 Scenario Development for Future Water Supply and Demand

Scenarios were developed by considering various factors that impact on future water security. The essential principle in WEAP is the establishment of scenarios. In WEAP the differences among the various scenarios could be considered against the baseline or reference scenarios. According to Addis Ababa City Planning Project Office (AACPPO, 2014), the low population growth scenario is about 2.5 % and the high population growth scenarios is about 3.3 %. For this study, two scenarios for population growth rates are used. The first scenario is the reference period or the base scenario, which is 2.5 % per year. The second scenario is the High population growth scenario, which is 3.3 % per year. The 3rd is climate change scenarios with result of urban climate projection under both RCP 4.5 and RCP 8.5, which will be used in WEAP as climate change impact assessment. The activities performed include (see Fig.5.2 schematic representation), incorporation of domestic, non domestic water use demands, and inserting climatic and hydrologic parameters. Also the assessment of the different management options that correspond to scenarios will be demonstrated using WEAP model. Scenarios method was built in WEAP, and then their impacts on water supply and unmet water demands in the city were assessed for future planning.

The proposed planning management options for the different scenarios were assessed using WEAP model. The interval between 2013 and 2039 were used as the planning period. The main factors of uncertainties for supply of and demand for water are climate change and population growth rate as well as socio economic improvements that imply increased level of both domestic (or household) and non-domestic consumption including industrial and commercial uses.

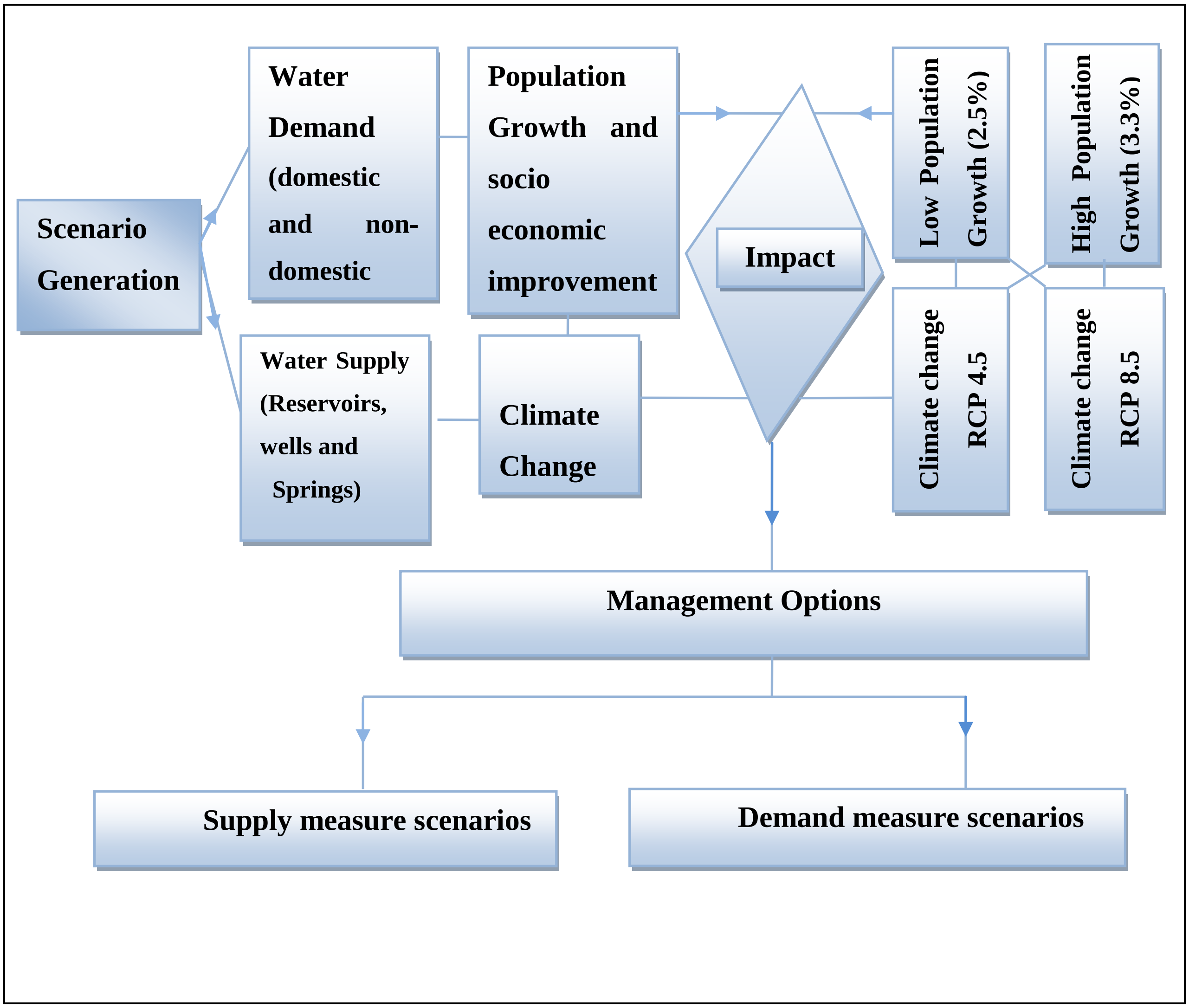


Figure 5. 2: Diagram of WEAP model scenarios and the management options.

5.2.3 Limitation

Water quality is not included in the study because of lack of data and therefore the study will focus on water quantity in relation to urban population and climate change.

5.3 Result and Discussions

5.3.1 WEAP comparison of water consumption

Comparison was made using distribution of total observed water consumptions data from AAWSA and WEAP generated data using key assumptions with respect to 2012 base period as shown in Fig.5.3. The comparison made between simulated WEAP water consumption data for the year 2012 and the observed data at the various demand sites shows WEAP assumes that all of the water supplied will reach the demand site. As there is a data gap regarding water loss or leakage for each demand site, WEAP's result for total consumption of the city is found to be 112.2 million m^3. As also confirmed in AWSSA's year 2012 business plan, from a total of 112 million m^{3}of water produced, only 66 million m^3 (60.15 %) was actually consumed, whilst the remaining 34 million m^3 (39.85 %) was lost.

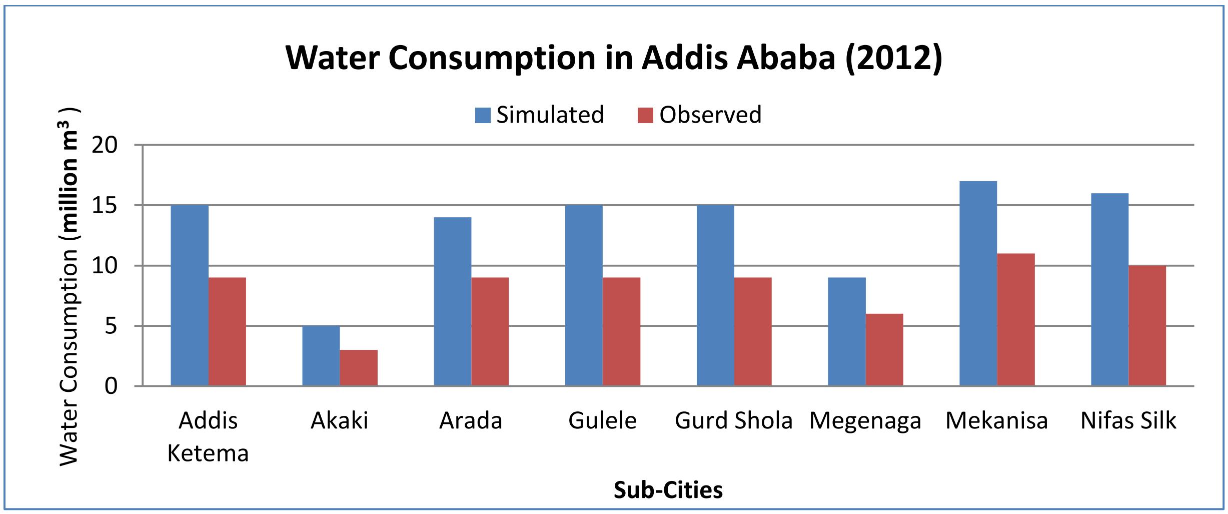


Figure 5.3: Observed water consumption of Branches versus WEAP generated data for water consumption (2012).

5.3.2 Observed Water consumption

The data obtained from AAWSA's water customer's information (2012) shows an upward trend in demand in the year 2012. The total number of connections has increased by 96,140 between 2005 and 2010, indicating an annual growth rate of 8.3 %. Non-domestic clients exhibited an annual growth of 2 % during the period. The total population of Addis Ababa in 2011 was 2,979,615 with 697,815 housing units. The 2012 Addis Ababa total connected customers both domestic and non-domestic were 327,996. The total observed domestic and non-domestic water consumption for the year 2012 was 66.7 million m^3. By looking at the total consumption and estimated total population of the city, the city's water consumption (demand) is found to be 110 l/c/day which is more or less similar with the observed data for 2012 that is obtained from AAWSA.

Table 5.5: Domestic and non-domestic water consumption (m^3) in 2012 (source AWSSA, 2012).

Sub-cities	Number of Domestic customer connected	Number of Non Domestic customers connected	Total connected customers	Estimated total Pop. of Addis Ababa	Domestic and Non Domestic water customers consumptions
Addis Ketema	40338	5407	45745	407130.5	9,295,491
Akaki	12825	3307	16132	143574.8	3,278,384
Arada	35163	7735	42898	381792.2	8,746,697
Gulele	40462	5363	45825	407842.5	9,312,693
Gurd Shola	41695	4859	46554	414330.6	9,460,820
Megenaga	23515	4491	28006	249253.4	5,704,773
Mekanisa	47010	5181	52191	464499.9	10,629,112
Nifas Silk	45166	5479	50645	450740.5	10,290,155
Sum	**286174**	**41822**	**327996**	2919164	**66,718,124**

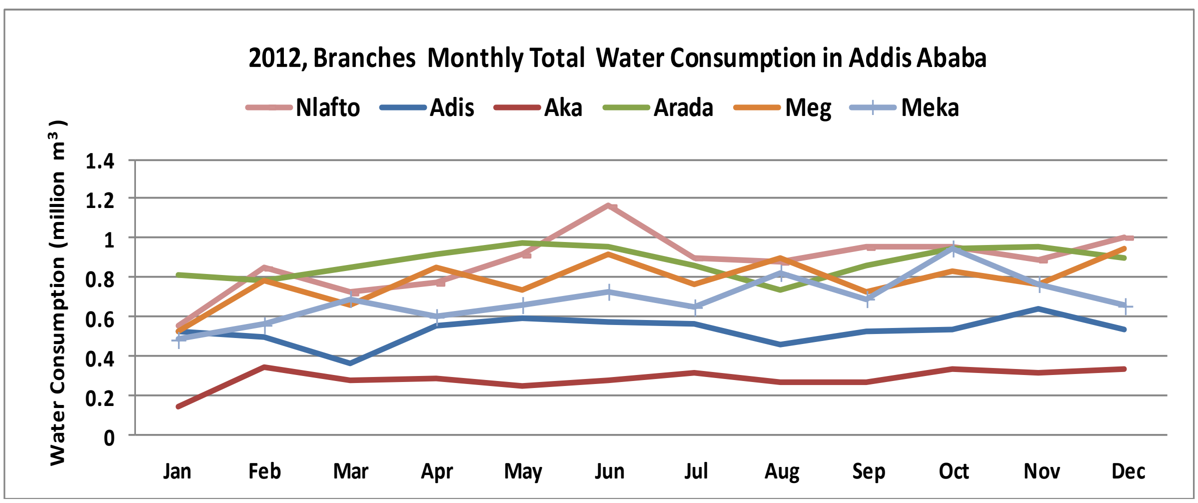


Figure 5.4: Branches monthly water consumption (2012).

Table 5.6 Monthly water consumption (m^3) in 2012.

Sub-city	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Addis K	531,914	498,525	557,734	653,794	592,987	573,741	562,435	455,418	528,319	533,808	641,861	534,877
Akaki	368,161	343,337	374,152	384,833	247,247	372,738	310,225	264,673	271,267	328,524	309,749	328,648
Arada	866,278	881,406	848,988	976,130	974,766	958,148	856,415	736,657	847,429	848,720	740,671	797,717
Gulele	594,265	686,447	568,651	590,165	536,932	739,142	800,718	588,269	595,536	526,310	676,582	540,369
Gurd Shola	921,066	841,611	950,520	863,083	660,043	774,061	713,211	831,751	996,908	736,101	744,924	835,116
Megenaga	792,043	781,473	860,261	859,054	738,197	816,735	779,419	894,860	764,423	733,140	773,752	962,245
Mekanisa	492,765	658,163	691,662	599,075	660,753	808,264	837,813	823,164	881,147	846,567	637,738	776,025
Nifas Silk	895,105	946,922	935,583	966,958	913,178	1,162,725	899,105	977,176	952,182	854,159	878,174	1,003,751
Total	5,461,597	5,637,884	5,787,551	5,893,092	5,324,103	6,205,554	5,759,341	5,571,968	5,837,211	5,407,329	5,403,451	5,778,748

The consumption levels in September, October, November, December, April, May and June are high. This shows that during dry seasons people consumed more than wet seasons. Also in all demand sites the consumption during August is much less than that of June (Fig. 5.4 and Table 5.6). During July and August and May the consumption rates are lowest in January, February and March. The combined domestic and non-domestic consumption of all demand sites and the monthly variations of rainfall at the demand sites in 2012 are given in Fig. 5.5. At the onset of rainy season in June, the consumption rate reaches its peak (Fig.5.5).

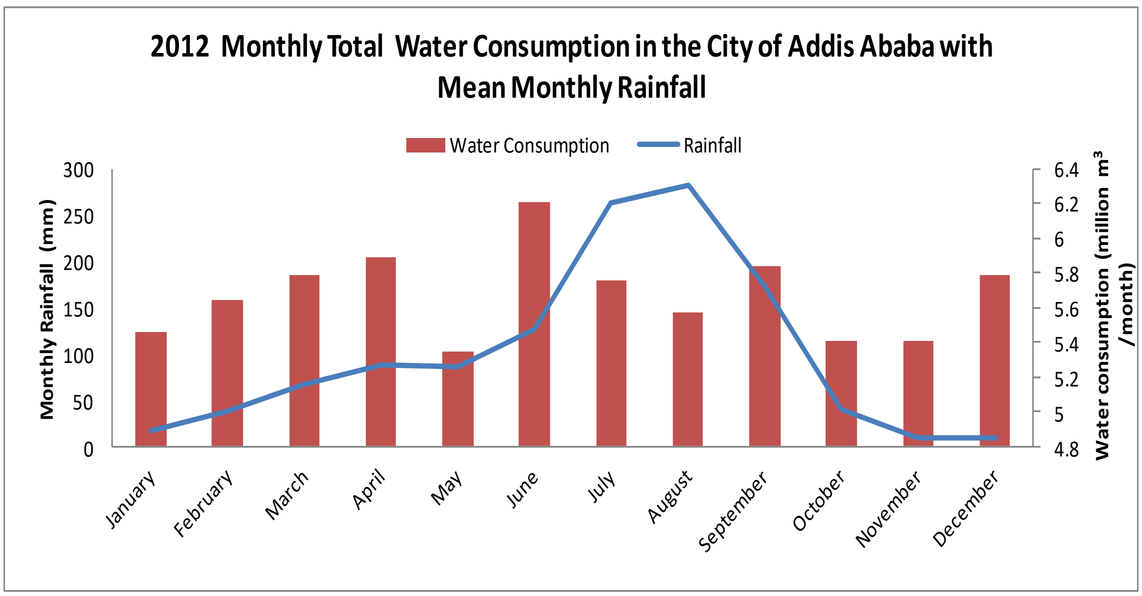


Figure 5.5: Monthly observed water consumption versus mean monthly rainfall (2012).

5.3.3 The Water Supply System

Water from Legedadi and Dire reservoirs is treated in Legedadi treatment plant and supplied to demand sites as an integrated water supply system. In this study discussions about the Legedadi reservoir refer to the Dire reservoir as well. The head flows of Gefersa and Legedadi rivers to the two reservoirs are high during July-October (Fig. 5.6a). Head-flow represents the average inflow from rivers to the first node of a reservoir. Input data used to calculate inflow are daily values of precipitation obtained from stations representing the catchments under consideration. In this study, the inflow is calculated by a reverse water balance approach and calibration for all catchments is considered as observed inflow.

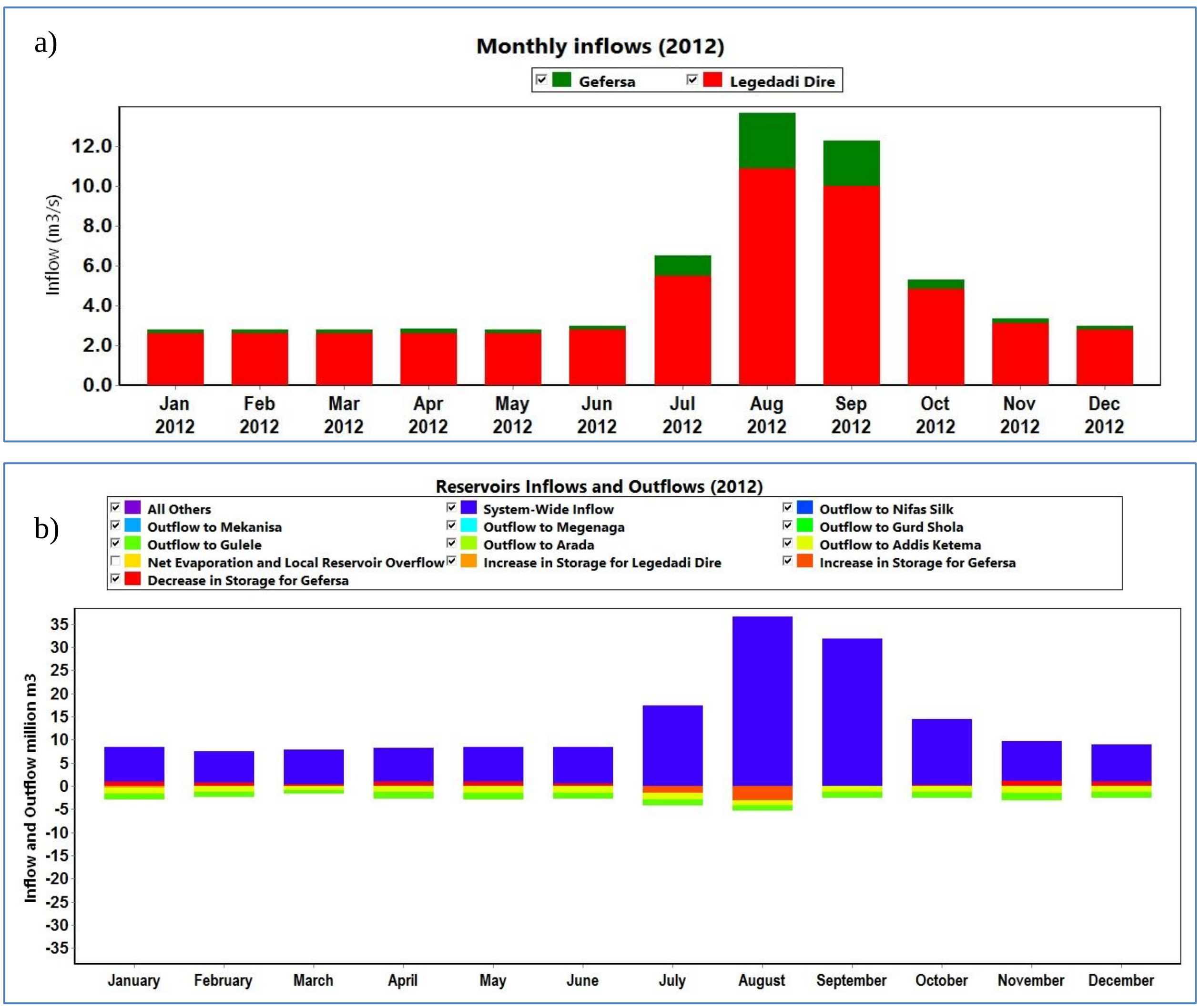


Figure 5.6: WEAP generated reservoir a) monthly inflow and b) inflow and out flow of reservoirs in million m^3 (MCM) for the year 2012.

The return flow is the total outflow of water (in percentage) and the amount of water being returned into the river or the underground aquifer systems. In the case of Addis Ababa only 7% of the waste water is linked to a sewerage system, the remained return to nearby rivers and aquifers. Fig. 5.6-b shows the inflow in the reservoir (positive values) and outflows from both Legedadi and Gefersa reservoir (negative values) in 2012. The comparison between the inflow and outflow values of each month shows that enough water is available in the system with distinct seasonal differences between wet and dry seasons of 2012. These results do not take into consideration the water cumulative effect of the reservoir.

5.3.3.1 Elevation Curve of Legedadi

Elevation-Volume Curves for the Legedadi Reservoir were prepared in 2010 (AAWSA, 2011). At the maximum water level, a total volume of 42.17 million m^3 was obtained for the year 2010 (Fig. 5.7). For the same elevation in 1998 the volume was calculated to be 43.8 million m^3. This indicates a reduction of 1.7 million m^3 due to siltation. From the storage elevation graph (Tahel, 2000), the maximum water level for the 1998 data of Gefersa reservoir is equals a storage volume of 12.8 million m^3. According to AAWSA (2011) Gefersa reservoir was upgraded and has the maximum storage volume as 35 million m^3 in 1994.

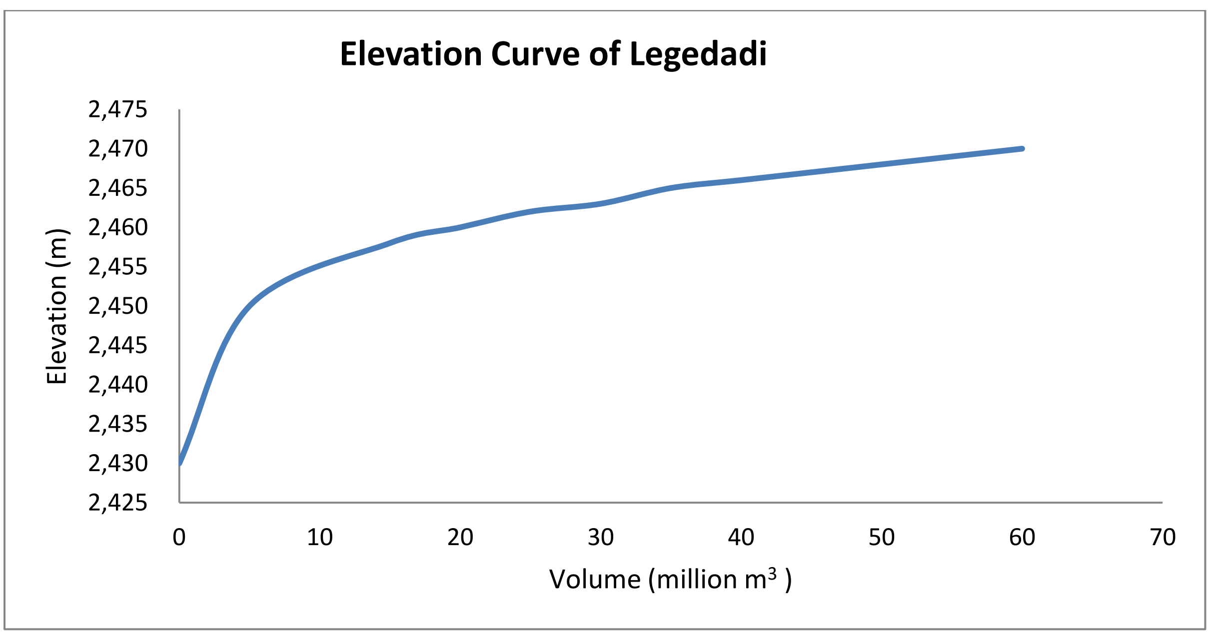


Figure 5.7: Elevation Curve of Legedadi (2010).

5.3.3.2 Reservoir Evaporation

The reservoir water balance or net evaporation were analyzed using daily and monthly data from Legedadi and Gefersa rainfall stations and the evaporation pans record of Legedadi and Gefersa. The result shown in Fig. 5.8 presents that a higher rate of evaporation is recorded in February, March and November. Evaporation accounts for 918 to 1,100 thousand cubic meters for Legedadi reservoir. Negative values indicate increases in water quantities in the reservoirs.

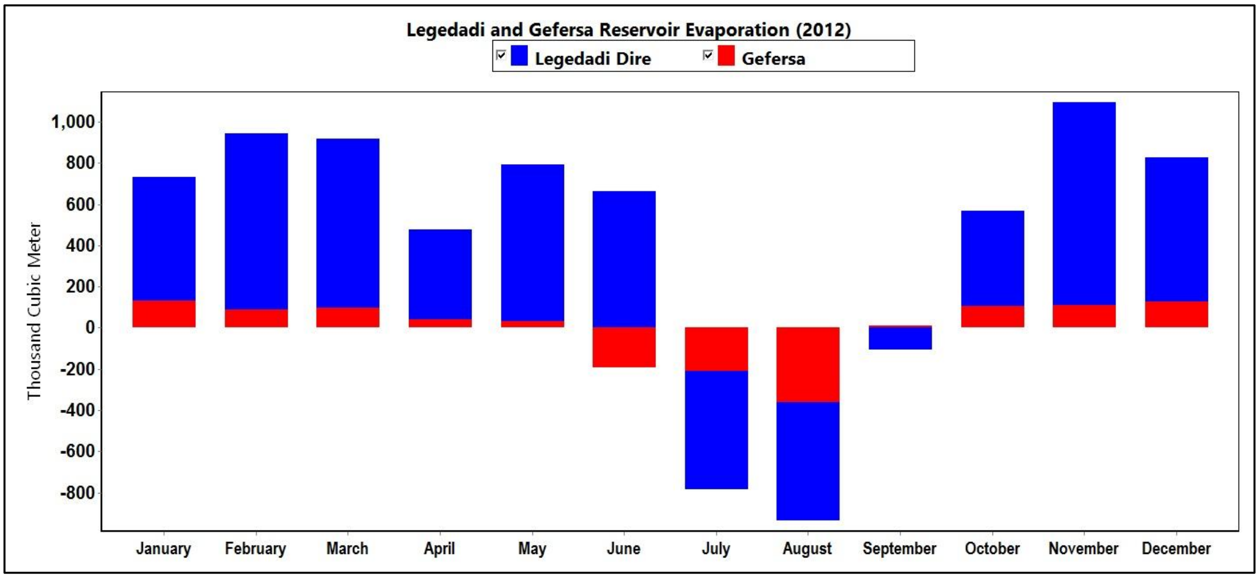


Figure 5.8: Monthly Reservoirs Evaporation for both Legedadi and Gefersa (2012).

5.3.3.3 Return Flow

In order to inform WEAP the extent to which the demand is satisfied, the user needs to connect the return flow from the demand sites. The return flow is a percentage of water for the total outflow and this value represents the quantity of water going back into river systems or underground aquifers. In the case of Addis Ababa, only 7 % of the waste water is linked to the city's sewage system, whereas the remainder of the return flow from the demand sites enters nearby rivers.

5.3.3.4 Water Balance Legedadi

Table 5.7 shows the inflow in the reservoir (positive values) and outflows from the reservoir (negative values). The comparison between the inflow and outflow values for all months shows the availability of surplus water in the system; however, the water supply is strained during the

Bega or the Dry season, especially during April, May and December. These results do not take into consideration the cumulative water shortage in the reservoir during the different months.

Table 5. 7: Legedadi Water Inflow with demand in (MCM) for the year 2012.

Legedadi (10^6 m^3)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
Inflow from up stream and Dire reservoir	6.96	6.26	6.99	6.76	6.93	7.18	14.73	29.19	25.94	12.99	8.03	7.52	139.5
Out flow to all Demand site	3.1	5.3	6	6.2	6.1	6.4	7.7	6.2	6.2	7.4	6.9	6.7	74.5
The balance of Bulk Water	3.86	0.96	0.99	0.56	0.83	0.78	7.03	22.99	19.74	5.59	1.13	0.82	65.0

Based on comparisons made between the amount of inflow and outflow for each month (2012), it is observed that sufficient water is available from July till October, but in most other months water levels are more stressed due to high consumption. These results do not take into consideration the typical cumulative storage effects of reservoirs. This research considered that it is necessary to define risk indicator values for each reservoir as a critical threshold values which will represent the limit of water available in the case of a very dry year. Based on WEAP functions, the inflows of a very dry year represent 50 % less than the inflows of a normal year. Comparing the cumulated inflow during the dry season of the year 2012 (blue area) and the cumulated out flow (red brown area) affirms that, at the current use and supply ratios, it is not necessary to implement new measures for bulk storage of water in order to assure water security for Legedadi water supply system.

5.3.3.5 Water Balance of Gefersa

The distribution of the inflow and outflow of Gefersa reservoir is shown in Table 5.8 When the inflow and outflow for each month are compared, it is observed that water availability is sufficient during July till September, but in most other months a water deficit occurs. The net result is a deficit of 0.35 million m^3 of water. These results do not take into consideration the cumulative effects of the reservoir. As can be seen in Table 5.8, the annual inflow into Gefersa reservoir is about 21.45 million m^3. It was noted that the monthly inflow in the reservoir varies from 7.37 million m^3 (maximum value) in August to 0.48 million m^3 in February. There is a shortage in net water supply availability in 2012 as the total demand is greater than the reservoir inflow.

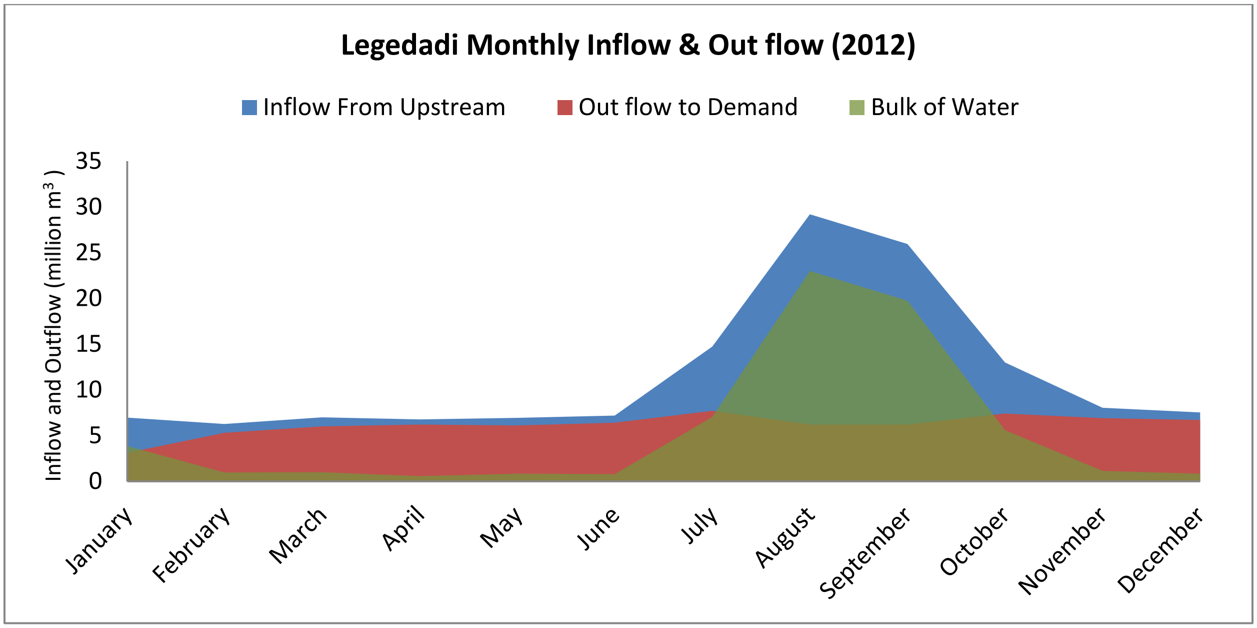


Figure 5. 9: Legedadi reservoir cumulated water balance 2012.

Table 5.8: Gefersa inflow with demand for the year 2012.

Gefersa (10^6 m^3)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
Inflow	*0.5*	*0.48*	*0.5*	*0.5*	*0.5*	*0.6*	*2.68*	*7.37*	*5.83*	*1.21*	*0.6*	*0.5*	*21.45*
Demand	*-1.2*	*-1.2*	*-0.8*	*-1.3*	*-1.4*	*-1.4*	*-1.36*	*-4.51*	*-5.25*	*-1.28*	*-1.5*	*-1.3*	*-22.73*
Bulk of Water	*-0.7*	*-0.7*	*-0.3*	*-0.8*	*-0.9*	*-0.8*	*1.32*	*2.86*	*0.58*	*-0.07*	*-0.9*	*-0.8*	*-1.28*

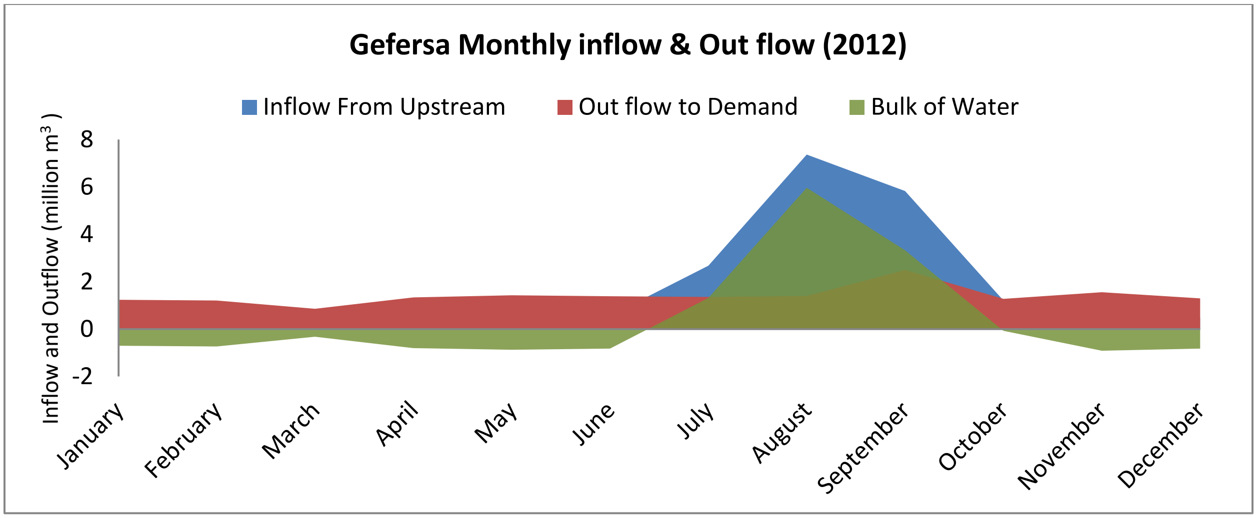


Figure 5.10: Cumulated water balance of Gefersa (2012).

The comparison of the cumulated inflow for the year 2012 (Blue area) and the cumulated outflow to demand sites (Red-brown area) affirms that during 2012 there was no water scarcity at the Geferssa water supply system.

5.3.4 Future Water Demand under Low Population Growth Scenario

With 2.5 % population growth rate, the WEAP predicts the population of Addis Ababa to be 5.5 million by 2039. The total demand in this scenario would grow from 110 million m^3 in 2012 to 664 million m^3 in the year 2039.

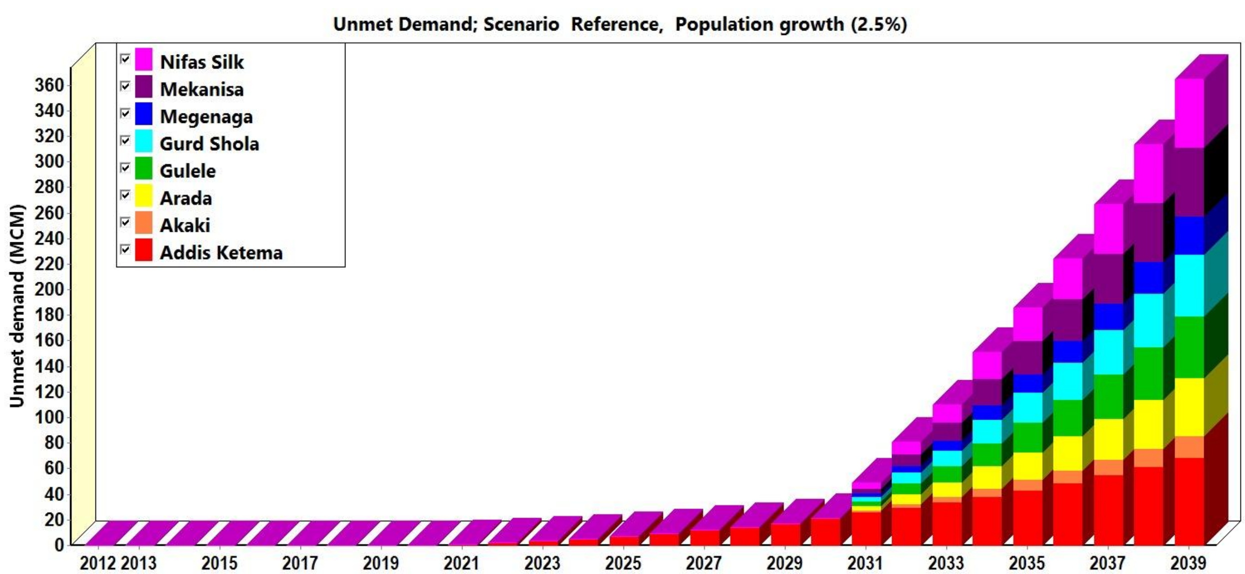


Figure 5.11: Annual unmet demand in million m^3 (MCM) for low population (2.5 %) growth scenario.

The key assumption is that the consumption per capita is anticipated to increase from 110 l/c/day in 2012 to 135 l/c/d by 2039. In this case, the result shows an increase in demand as the population grows. The water availability under low population growth scenario would result in insufficient amount of water supply in some sub-cities. As a result, the unmet demand is estimated at about 364.77 million m^3 in year 2039 (Figure 5.11), whereby the supply- demand gap will be high in Addis Ketema (68.89 million m^3), Mekanisa (54 million m^3) and Nifas Silk (53 million m^3).

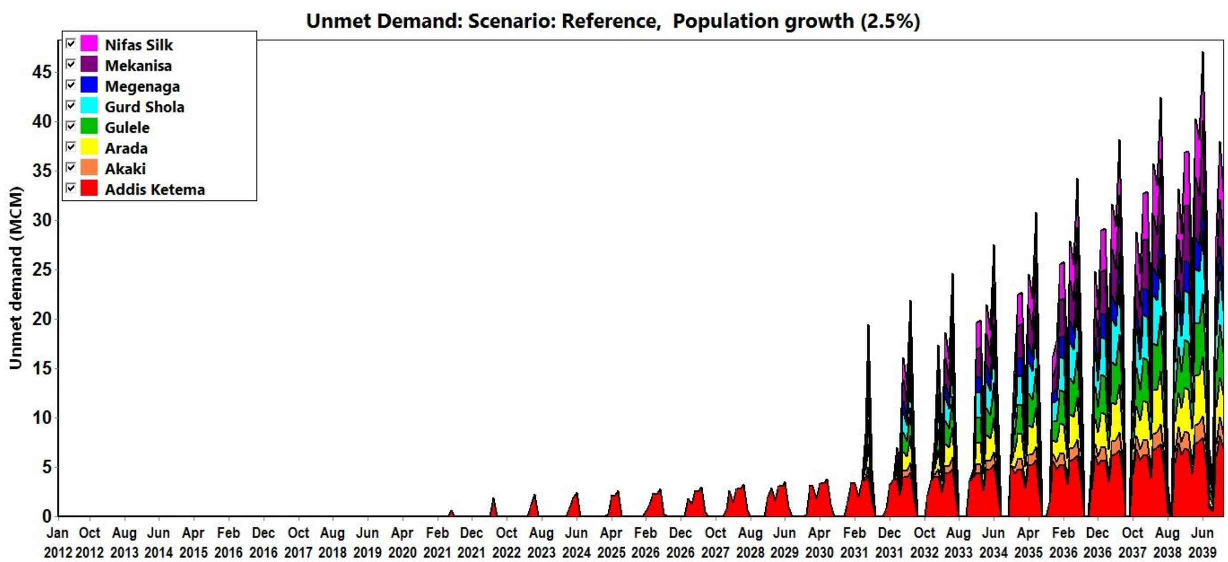


Figure5.12: Monthly unmet demand in low population (2.5%) growth scenario.

Monthly variation of unmet demand during the period from 2013 to 2039 shows that even under the low population growth scenario, the unmet demand is high during May to June in branches like Addis Ketema 2025 to 2039. The shortage of water in other branch like Arada, Gulele, GurdShola, and Mekanisa and Nefasilk Laafto will be high during April to July 2035 to 2039 (Fig.5.12).

5.3.5 Future water demand with high population growth scenario

According to the WEAP model, the projected population for Addis Ababa under the high population growth scenario (3.3 % per year) is about 7 million by the year 2039 (Fig.5.13). The impact of high population growth on water demand is reflected in the increase from 233 million

m^3 in 2025 to 686 million m^3 in 2039. This high demand also puts significant pressure on the storage volume of Legedadi and Gefersa reservoirs.

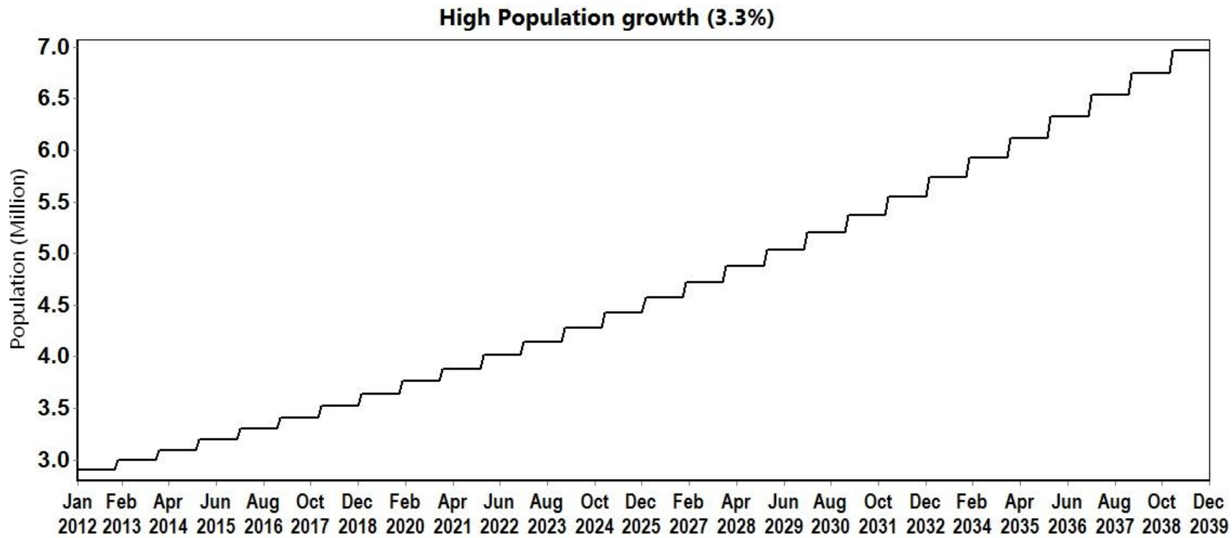


Figure 5.13: All Sub-City population growth at 3.3%.

The water availability under high population growth would cause greater insufficiency of water in some sub-cities. As a result the unmet demand is estimated at about 430.84 million m^3 in the year 2039 (Fig. 5.14), with the highest supply-demand gaps in Addis Ketema (75.64 million m^3), Mekanisa (65 million m^3) and Megenaga (34 million m^3)

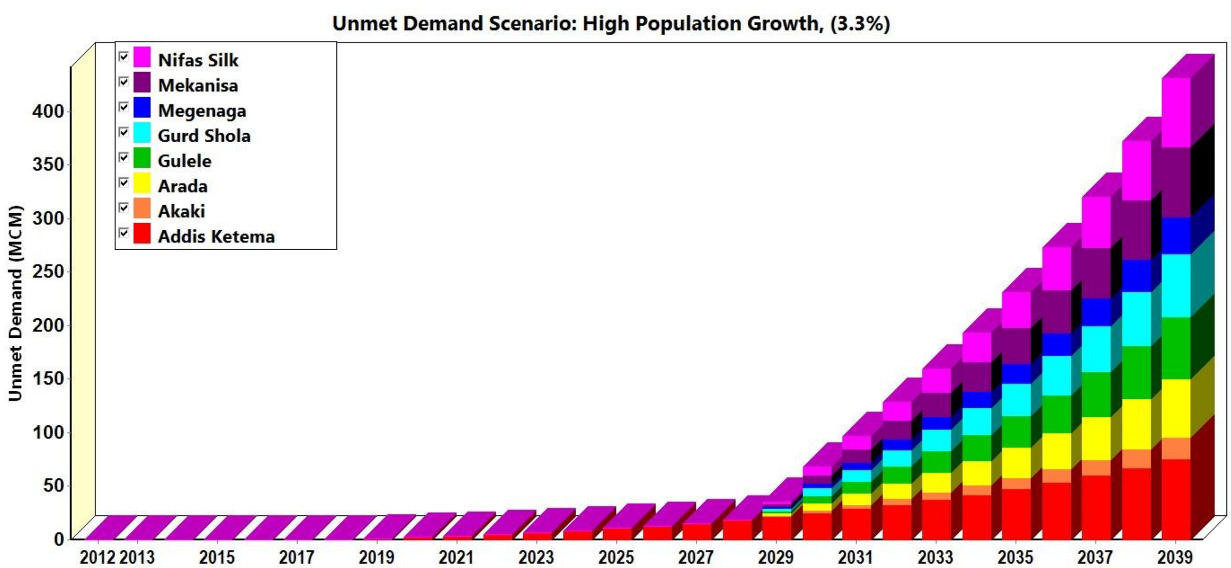


Figure 5.14: Projected annual total water demand in high population (3.3 %) growth scenario.

Fig. 5.15 shows monthly variation of unmet demand during the period from 2013 to 2039 shows that even under the high population growth scenario, the unmet demand is high during May to June in branches like Addis Ketema 2021 to 2039. The shortage of water in other branch like Arada, Gulele, GurdShola, and Mekanisa and Nefasilk Laafto will be very high and will occur during November to March and April to July 2033 to 2039.

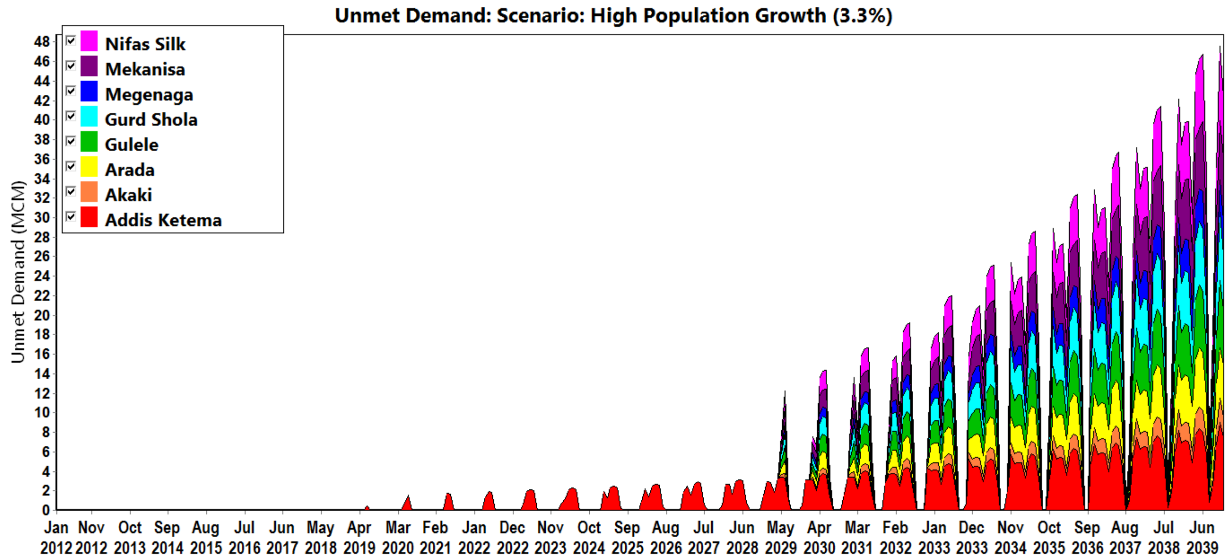


Figure 5.15: Projected monthly total water demand in high population (3.3 %) growth scenario.

5.3.6 Climate Change Scenario

The rainfall data from NIMR-HadGEM2-AO climate model under a midrange RCP 4.5 scenario and RCP 8.5 high emissions scenario for 2030s have already been corrected for possible biases (Fig. 5.16). The performance of NIMR-HadGEM2-AO climate model scheme employed has been assessed for present climate using historical observational data and it has been reported in (Chapter 4). Fig.4.7-j shows the predicted magnitude of rainfall that is used for setting climate sequence for the years 2010-2039.

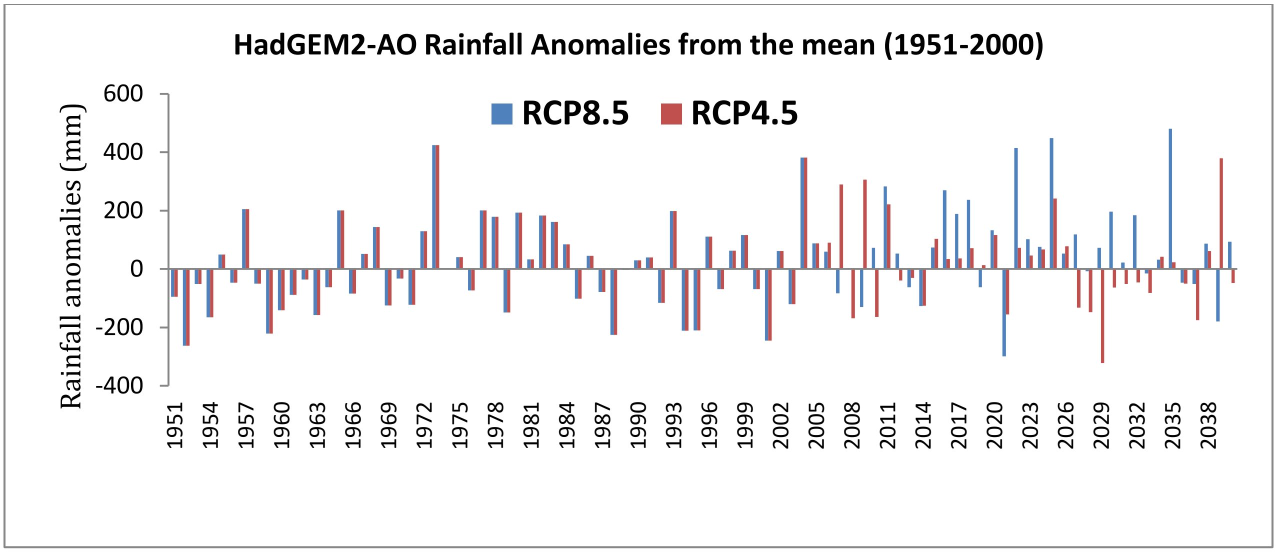
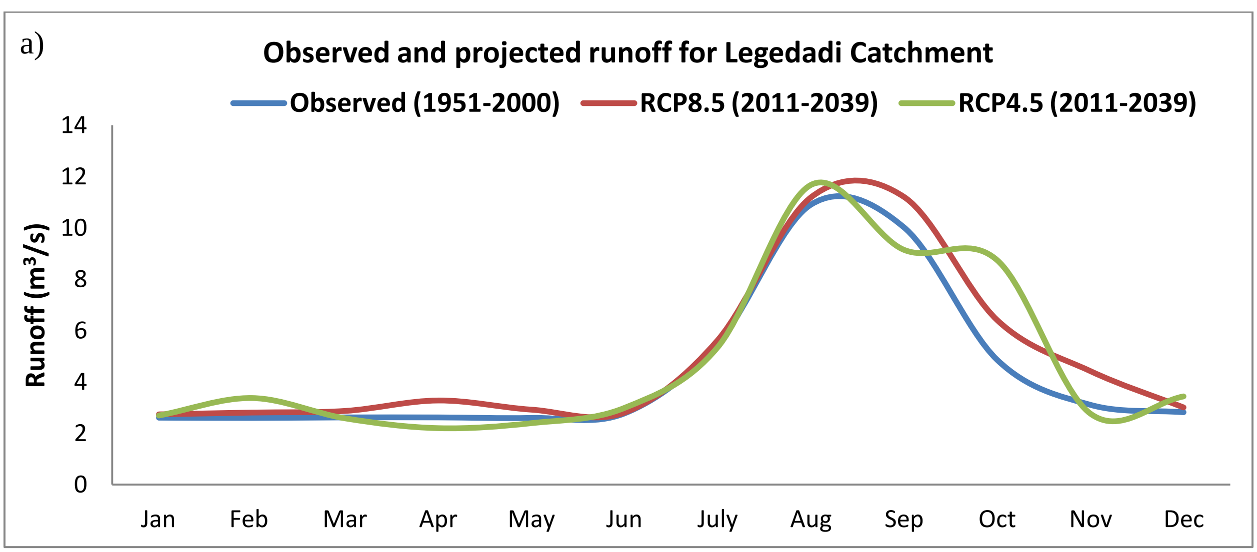


Figure 5.16: Addis Ababa average rainfall anomalies (relative to the 1951- 2000 average) for 1951-2040, under RCP 4.5 and RCP 8.5 Scenarios.

5.3.6.1 Future Runoff and Reservoir Evaporation

In order to estimate the future inflow of surface water, one of the input values that need to be considered is surface runoff. The result of Legedadi-Dire catchment, estimate the future surface runoff for the period 2030s (2010-2039) time horizons to peak during Kiremt (rainy season) with an observed catchment runoff of 10.9 m^3 / s. This will increase to 11.2m^3 / s with the RCP 8.5 scenario (see Fig. 5.17a). In case of Gefersa, the inflow will also increase up to 2.8 m^3 / s with the RCP 4.5 emission scenario (see Fig. 5.17b).



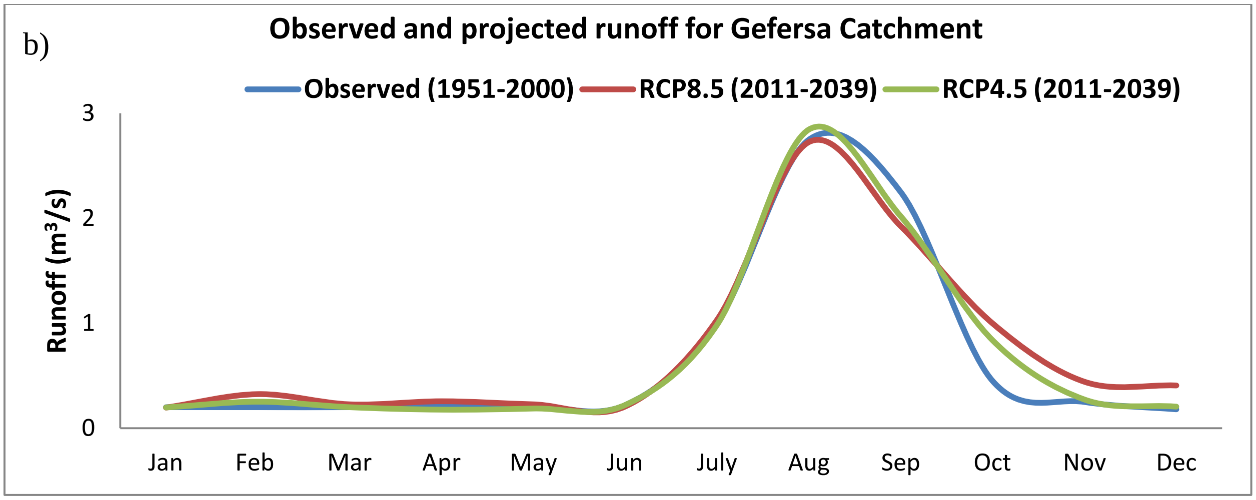
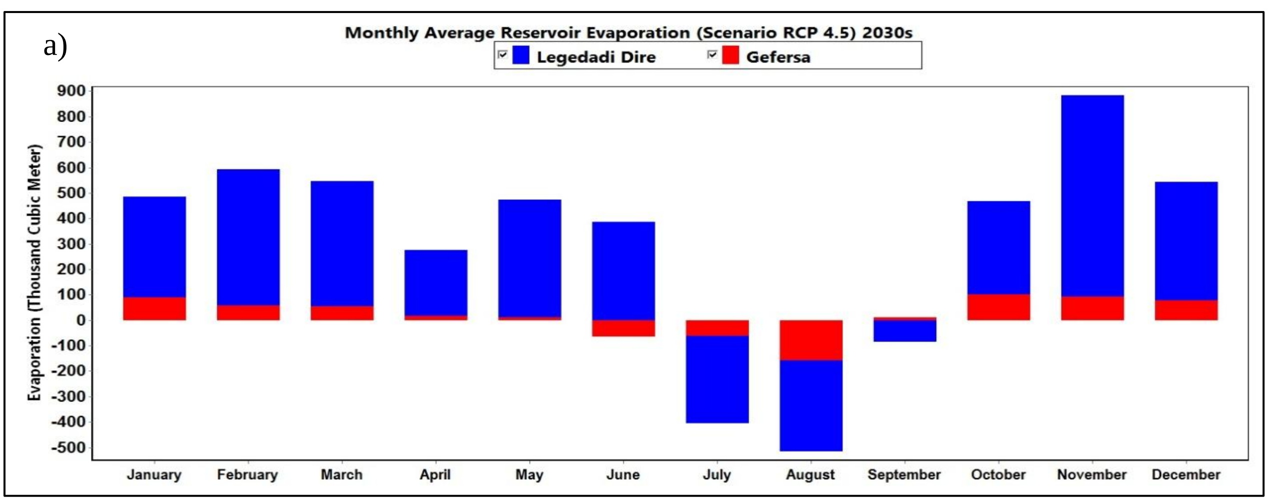


Figure 5.17: Observed and projected runoff of a) Legedadi and Dire (2011-2039) and b) Gefersa (2011-2039).

The created year sequence consists of the sequence of climatic variation for the scenario period. Each year of the period is assigned to RCP4.5 and RCP8.5 climate scenarios. Reservoir evaporation is also important for future water availability in climate change and negative evaporation indicates an increase in water (SEI, 2014). The projected result shows that an increase in evaporation is expected during the dry season from November to December and February and decrease during rainy season in both RCP 4.5 and RCP 8.5 because of increase in rainfall and high cloud coverage during July and August (see Fig. 5.18 a-b).



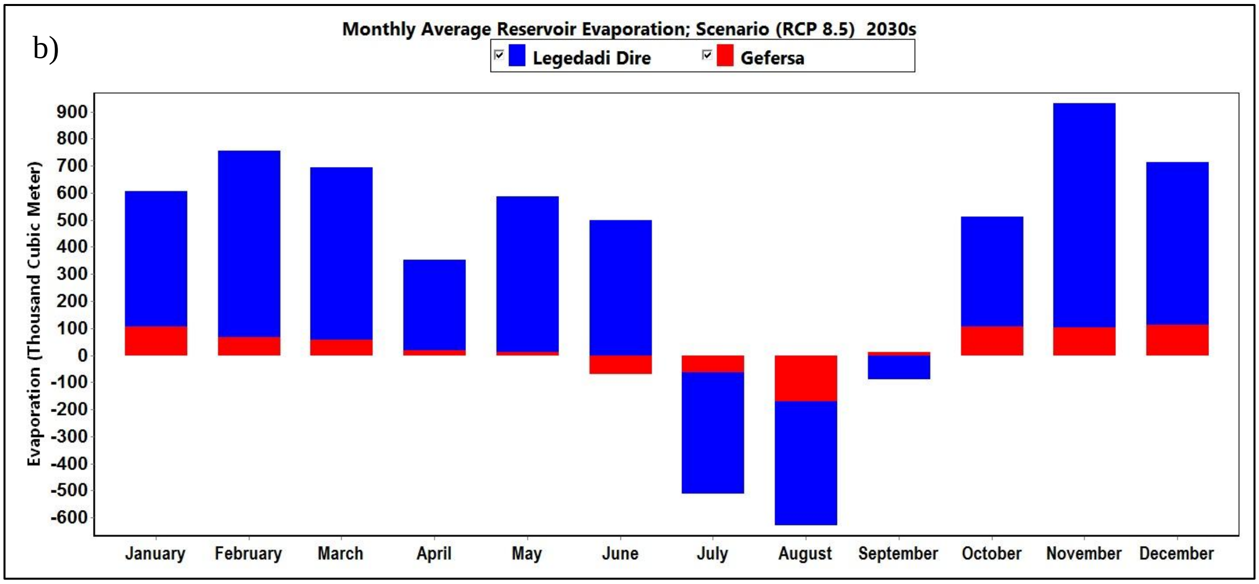
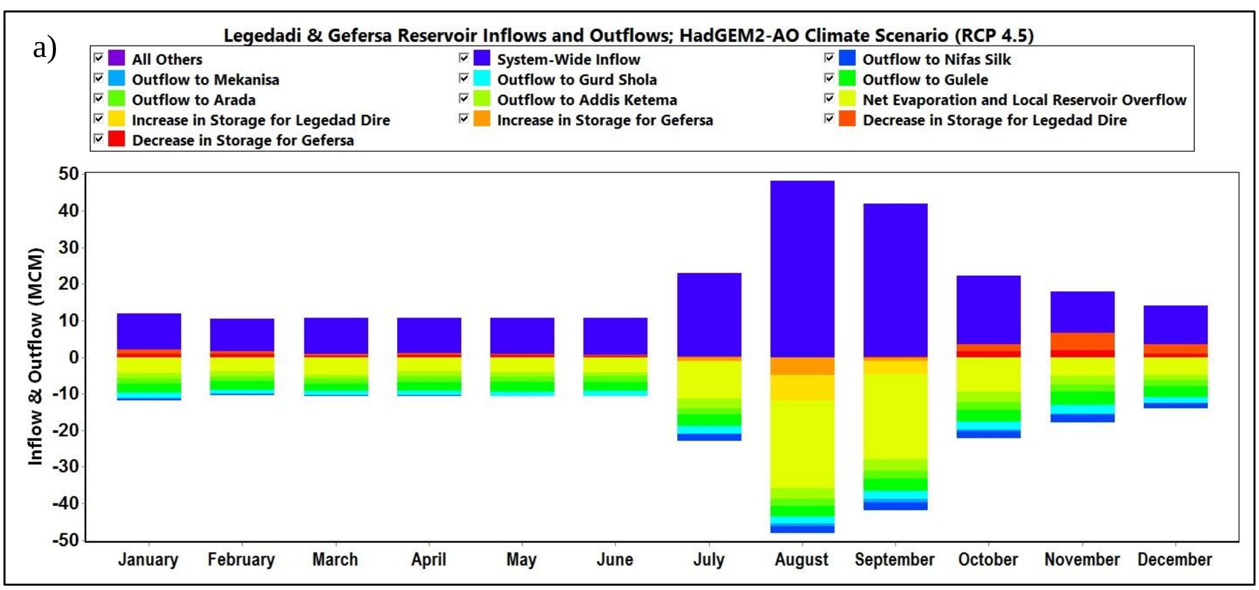


Figure 5.18: Monthly Average Reservoir Evaporation for both Legedadi and Gefersa with a) RCP 4.5 and b) RCP 8.5 for 2030s (2010-2039).

5.3.6.2 Impact of Climate Change on Water Supply

The comparison between the inflow and outflow values for each month shows that there is enough water in the reservoirs under RCP-8.5 scenario during the rainy seasons of July, August and September and there will be shortage during the dry months of November, December, January and May.



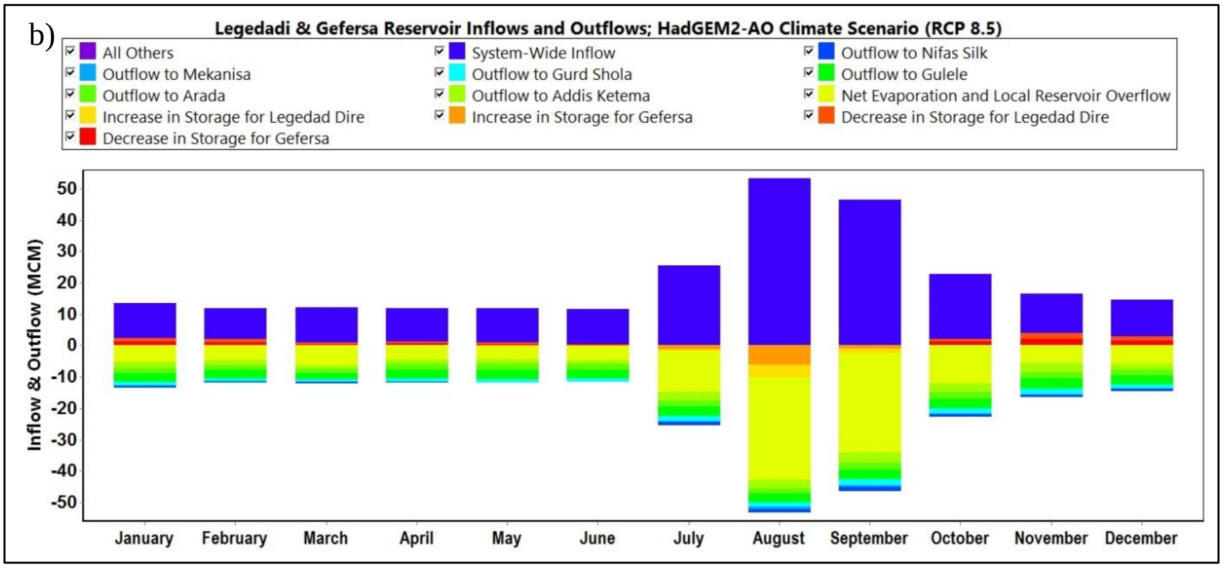


Figure 5.19: a) Average monthly storage inflow/outflows of Legedadi and Gefersa reservoirs under RCP 4.5 scenario and b) Average monthly storage inflow/outflows of Legedadi and Gefersa reservoirs under RCP 8.5 scenario 2030s (2010-2039).

The future reservoir inflow of Legedadi and Gefersa (i.e. during 2010-2039 period) calculated under both RCP 4.5 and RCP 8.5 scenarios indicate that the offset of the Kiremt or the long rainy season inflow in September is slightly decreased. This result will affect the monthly demand in the various sites.

Table 5.9: Combined reservoirs inflow and outflow with a) RCP 4.5 and b) 8.5 Scenarios in million m^3.

(a) Legedadi and Gefersa Reservoirs (2010-2039) RCP 4.5 Scenario													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**
System-Wide Inflow	9.9	8.9	9.9	9.6	9.9	10.2	22.9	48.2	41.9	18.7	11.4	10.6	212.0
Outflow to Demand site (MCM)	-7.3	-6.4	-5.9	-6.7	-6.6	-6.6	-11.5	-12.2	-14.1	-12.8	-12.9	-9.2	-112.1

Net Evaporation & overflow	-4.5	-4.0	-4.9	-4.0	-4.1	-4.1	-10.2	-24.0	-23.2	-9.4	-5.1	-4.9	-102.4
Bulk of Water (MCM)	-1.9	-1.5	-0.8	-1.1	-0.8	-0.5	1.2	11.9	4.6	-3.5	-6.5	-3.5	-2.5

(b) Legedadi and Gefersa Reservoirs (2010-2039) RCP 8.5 Scenario in MCM													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**
System-Wide Inflow million m^3	10.9	9.8	10.9	10.6	10.9	11.3	25.3	53.2	46.3	20.6	12.6	11.6	234.6
Outflow to Demand site million m^3 **(MCM)**	-7.9	-7.2	-5.5	-7.2	-7.3	-7	-10.4	-10.4	-12.2	-10.6	-10.9	-8.7	-105.7
Net Evaporation & overflow	-5.3	-4.7	-6.1	-4.5	-4.6	-4.6	-13.2	-32.8	-31.77	-12.1	-5.6	-5.7	-131.3
Bulk of Water million m^3	-2.3	-2.1	-0.7	-1.2	-0.9	-0.3	1.7	10	2.3	-2.1	-3.9	-2.8	-2.5

A 2013-2039 monthly distribution of the inflow and outflow of Legedadi and Gefersa reservoirs under RCP 4.5 and RCP 8.5 scenarios can be seen in Table 5.9. The comparison between the inflow and outflow values for each month shows that, with the RCP 8.5 scenario there is enough water available in the system during the rainy seasons of July, August and September, whereas shortage occurs between November to December and January to May which are the dry seasons. Table 5.9b shows that the inflow under the RCP 8.5 scenario is higher than what is to be found under the RCP 4.5 scenario which satisfied all its demands. However, the RCP 8.5 scenario shows that there is a shortage of up to 3.9 million m^3 of water in November. A comparison between the inflow and outflow values of each month, we can observe that we will have enough water available in the system only during July, August and September indicating the need for more water.

5.3.6.3 Population growth and climate change impact on water demand

Table 5.10 shows the annual unmet demand for RCP4.5 and RCP 8.5 with low (2.5 %) population growth scenarios. The result of the RCP 8.5 scenario with low population growth shows that the unmet water demand will be 11.75 million m^3 in 2030, 49.6 million m^3 in 2035 and 257.28 million m^3in 2037. The result of the RCP 4.5 scenario with low population growth shows that the unmet water demand will be 76.09 million m^3 in 2030, 103.23 million m^3in 2035 and 314.91 million m^3in 2037. This indicates that most of the years the unmet water demand with RCP 4.5 climate change scenario is higher than that of RCP 8.5 scenario.

However, the projected rainfall for the year 2039 will expected to be very wet in RCP 4.5 and very dry in RCP 8.5 (see Fig. 5.16). As the result the annual unmet demand for RCP8.5 and RCP 4.5 with low (2.5 %) population growth scenarios will be 372.8 million m^3 and 168.13 million m^3 respectively for the year 2039. The RCP 4.5 scenario with high population growth (3.3 %) shows that the unmet water demand will be 87.42 million m^3 in 2030, 158.38 million m^3 in 2035 and 380.72 million m^3in 2037. In addition, the result of the RCP 8.5 scenario with high population growth (3.3 %) shows that the unmet water demand will be 13.40million m^3 in 2030, 78.51 million m^3 in 2035 and 319.94 million m^3 in 2037. The annual unmet demand for RCP 8.5 and RCP 4.5 with high (3.3 %) population growth scenarios will be 462.77 million $m^3$and 261.72 million m^3 respectively in 2039. This indicates that the unmet water demand in both high population growth and the dry climate of RCP 4.5 & RCP 8.5 climate change scenario will lead to substantial shortage of water in the city.

Table 5.10: Unmet Demand comparisons with six Scenarios.

Scenarios	Unmet Water Demand (million m^3 /year)								
	2012	2015	2020	2025	2027	2030	2035	2037	2039
Reference (2.5 %)	0.0	0.0	0.0	7.26	11.82	21.41	185.71	266.65	364.77
High Population Growth (3.3 %)	0.0	0.0	0.0	10.54	15.41	67.90	231.02	319.95	430.54
Climate Change (RCP 4.5) with pop. growth (2.5 %)	0.0	0.0	0.0	3.76	12.62	76.09	103.23	314.91	168.13
Climate Change (RCP 8.5) with pop. growth (2.5 %)	0.0	0.0	0.0	3.21	6.78	11.75	49.66	257.28	372.87
Climate Change (RCP 4.5) with pop. growth (3.3 %)	0.0	0.0	0.0	4.35	14.22	87.42	158.38	380.72	261.72
Climate Change (RCP 8.5) with pop. growth (3.3 %)	0.0	0.0	0.0	3.77	7.65	13.40	78.51	319.94	462.77

5.3.7 Possible solutions to the projected water supply deficit

5.3.7.1 Demand-management through water tariffs

A pricing system based on efficiency criteria does not only aims for this level of service but also acts as a built-in regulator of demands and system growth as water supply management. For the demand management scenario the price of water starts at 0.12 USD / m^3 (ETB 2.60 / m^3), proposed to increase at a rate of 2 % per year. Also the demand management option considered here promotes water saving through seasonal water price increment. The result of these policy measures shows that the unmet demand under the high population growth (3.3 %) scenario and dry climate scenario of RCP 4.5 can be mitigated with only 6 million m^3 deficits.

5.3.7.2 Supply and Demand Measures

The impact of climate change on reservoir's storage volume, which is shown in Fig.5.20, will be managed and mitigated by supply measures that consist of upgrading or increasing the capacity of existing reservoirs and constructing new reservoirs. The catchment areas of both Legedadi and

Gefersa reservoirs are located in areas of high rainfall distribution. However, whilst the Gefersa reservoir has smaller capacity than that of Legedadi, the rainfall at Gefersa catchment is found to be higher. Thus, the expansion for Gefersa reservoir is highly recommended than that of Legedadi.

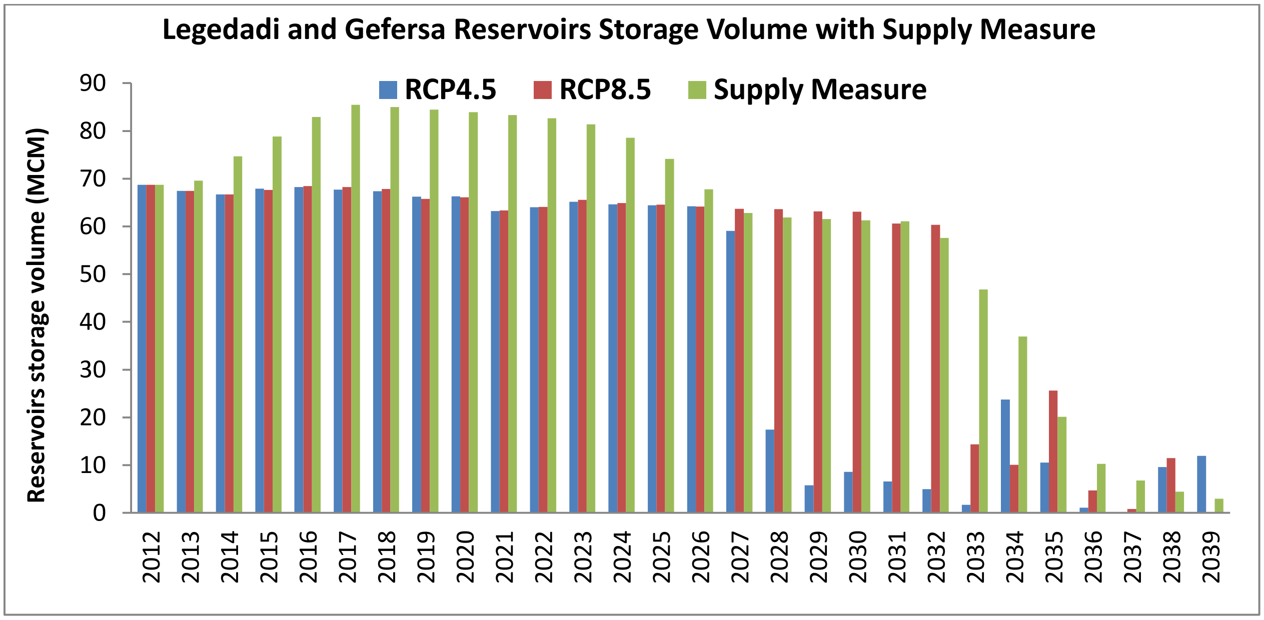


Figure 5.20: Supply Side Management Option for the Impact of Climate Change on the Storage Volumes of Legedadi and Geferssa Reservoirs.

According to AAWSA business plan (2012), an additional new reservoir (dam) will be constructed at Gerbi (29.2 million m^3 per year) by the year 2016, but not done yet, the Legedadi Reservoir will be upgraded to add 11 million m^3 by 2014, and new wells will be developed that will supply about 90.1 million m^3 from 2014 to 2020. This additional supply (a total of 130.3 million m^3) will be taken into consideration in management options as one of the supply measures. Fig. 5.21 shows that after upgrading the capacity of existing reservoirs, reducing leakages in water transmission lines from the current 34.3 % to 10 % and constructing new reservoirs with full capacity holding of water, there is a possibility to adapt to the future climate change impacts. With supply measure, there will be unmet deficit of 174.19 million m^3 for future domestic and non-domestic water demand (see Fig. 5.21).

Figure 5. 21: The unmet demand after demand and supply measures are employed.

5.4 Conclusion

Based on WEAP model, the population of Addis Ababa will increase to 5.5 million by 2039 at 2.5 % annual growth rate, which is the low population growth scenario. Given this projected population figure, there will be deficiency in water availability in some of the sub-cities. Under this scenario, the total demand would grow from 110 to 664 million m^3 by 2039. The consumption per capita is assumed to increase from 110 l/c/day in 2012, which is already below the standard set by WHO, to the standard of 135 l/c/day by 2020. As a result, the shortfall unmet demand is estimated to be 364.77 million m^3 in the year 2039, with the shortfall expected to be high in Addis Ketema (68.89 million m^3) and Mekanisa (54 million m^3). According to WEAP model, the size of the city's population when projected using the high population growth rate scenario (3.3 %) will be 7 million by the year 2039. This higher increase in population will have an impact on the aggregate water demand of the city that rises to 686 million m^3 in 2039. The reservoirs inflow under the RCP 8.5 scenario is higher than what is to be found under the RCP 4.5 scenario which satisfied all its demands. However, the RCP 8.5 scenario shows that there is a shortage of up to 3.9 million m^3 of water in November. Given current capacities and future plans to upgrade the city's water supply system, there will be sufficient water supply only up to 2027.

The results of the WEAP model for the RCP 8.5 scenario combined with the low population growth scenario shows that the unmet water demand will be 372.8 million m^3 by 2037. On the other hand, the result of the RCP 4.5 and low population growth scenarios suggests a deficit of 314.91 million m^3 by 2037. The model's result for the RCP 8.5 and high population growth (3.3 %) scenario shows that the unmet demand will be 319.94 million m^3 by 2037. This indicates that the highest volume of unmet water demand is expected to occur under the high population growth and dry climate years that will have big repercussions on water shortages in the city (Table 5.10).

To manage the water shortage, updating water tariffs is suggested as a better option with seasonal water price adjustments. Even after implementing the supply measures planned by AWSSA the future unmet demand for both domestic and non-domestic use will be 174.19 million m^3 (Fig. 5.21). Adopting a seasonal adjustment of water tariffs as well as the construction of new reservoirs and wells will contribute towards reducing the future unmet demand. It is therefore crucial to take measures aimed at ensuring the sustainability of the water sources by using the different research finding and options reported here. Particular attention should be drawn to optimize the supply and promote demand side management practices as workable climate change adaptation measures.

CHAPTER 6

INFLUENCE OF URBANIZATION-DRIVEN LAND USE CHANGE ON CLIMATE

6.1 Introduction

Urbanization usually transforms vegetative covered land into impervious gray infrastructure land cover (Xian, *et al.,* 2008). These different gray infrastructure urban land cover can have significant effects on local climate and weather (Wu and Murray, 2003; Zhou, *et al.,* 2004; Grimmond, 2006; Rizwan, *et al.,* 2008; Carter, *et al.,* 2015). Understanding urban landscape conversions and interactions between natural phenomena and human activities are important for proper land and climate change management (Mantyka-Pringle, *et al.,* 2013). Urban gray infrastructure of built up areas (which are basically manmade), the use of air conditioners and transportation systems bring additional heat sources into the urban layer (Wilby and Perry, 2006). Several studies have indicated that urban centers are warmer than their surrounding countryside leading to an increased urban heat island (UHI) (Babazadeh and Kumar, 2015; Suomi, 2014; Mohan, *et al.,* 2011). In contrast to the countryside, building materials and non-vegetated surfaces retain more solar energy during the day, and have lower rates of radiant cooling during the night time (Santamouris, 2013; Babazadeh and Kumar, 2015; Baklanov, *et al*., 2017). In urbanized areas the cooling process is made slower due to higher night-time air temperatures (Mohan, *et al.,* 2013; Oladide, *et al*., 2013). Different surface types with varying physical properties cause different rates of absorbed solar energy and re-radiation (Oke, 1987). The UHI intensity is observed to decrease with increased wind speeds and higher cloud coverage (Grimmond, 2006; Baklanov, *et al*., 2006; Fernando, 2013). UHI intensity is high during high pressure or anticyclone system or dry summer season (Kuttler, *et al*., 2007; Morris, *et al*., 2001). Increases in population density of a city will increases UHI intensity (CLUVA, 2010). A literature study revealed a scarcity of available studies on Africa in general and the absence of published detailed research to understand the impact of urbanization induced land use and cover change on climate. Therefore this study aims to assess how land use changes impacts on urban scale climate through UHI effects.

Urban population and industry growth, results in conversion of the landscape from natural to increasingly impervious urban land (Toy and Yilmaz, 2010; Kotharkar and Surawar, 2016). The consequence of this change will have major effects on the natural environment and climate.

Notable spatial expansion that accompanied population growth are developmental activities that includes infrastructure in roads, railway, building construction and others. The UHI resulted from an increase in urbanization of land modifying the micro-climate of the city (Hoffmann, et al., 2011). Therefore a study of the existing and possible future occurrence of UHIs in Addis Ababa could provide information that will prevent further negative developments.

The main aim of this chapter is to determine how urban land cover change influences climate in the city of Addis Ababa by means of Remote Sensing land cover data and spatial gridded climate data.

- ❖ Specific objectives are:
    1) To generate and classify land cover for the city through the use of remote sensing data and to determine the land cover change of the city within different time periods.
    2) To explore the influence of urban land cover change and population density on climate through analyzing the urban heat island (UHI) of the city and assess future UHI scenarios using statistical downscaling method (SDSM).

The structure of this chapter is as follows: Section 6.2 describes data and the methods employed. Section 6.3 presents result and discussion on the finding of land use and land cover changes using Land-sat images; investigations of the observed urban climate change and future Heat Island effects. Section 6.4 presents chapter conclusion and recommendation.

6.2 Data and Methods

6.2.1 Data

To assess land cover changes, three Land-sat images taken on clear cloud-free days were selected. Accordingly, images from Land-sat 5 Thematic Map (TM) sensors taken on: December 23, 1986; January 25, 1999 and January 10, 2011 were selected. All Land-sat TM images were accessed free of charge from U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) via http://glovis.usgs.gov web site. The data supplied by EROS

are geo-referenced using the Universal Transverse Mercator (UTM) map projection (Zone 37), WGS 84 datum and ellipsoid. The Land-sat TM grid cells size are 30 meter by 30 meter pixels.
Climate data of Addis Ababa observatory and Addis Ababa Bole International Air-port stations for the period 1960 -2001 are obtained from NMA. The spatial climate of Addis Ababa city is assessed using rainfall as well as minimum and maximum temperature data at 10 km by 10 km grid for a 20 years period from 1981-2010 obtained from the National Meteorological Agency (NMA) of Ethiopia. UHI is calculated for the years 1961-2001 using data obtained from NMA for Addis Ababa observatory (AAOBS) (an urban site) (9.01° N, 38.75° E)and Bole International Airport(8.98° N, 38.798° E) (AABIA) (for rural site) (see Fig. 2.6). For the future UHI, data from Global Circulation Model (GCM) HadCM3 under A2 and B2 scenarios for the period 1960-2099 were employed.A2 represents a diverse world with increasing global population and economic growth that is disjointed and slow (Nakicenovic & Swart, 2000); whilst B2 represents a scenario under which population grows on a continuous basis, accompanied by intermediate level of economic development.

6.2.2 Methodology

6.2.2.1 Land use change

Land cover denotes the physical land type such as forest or open water, whereas land use refers to how people are using the land (Carlson and Arthur, 2000). Land cover change in general and land use change in particular would have either direct or indirect impacts on the extent and conditions of changes that occur in the land surface as a whole. The changes could be transformation of land cover to land use or vice versa. The rate of change was calculated for each type of land use and land cover using the following formula:

$$Rate = \frac{(Re - Pr)}{Y}$$

Eq. (6.1)

where: *Re* = Recent area of land use and, or cover in km^2, *Pr* = Previous area of land use and, or cover in km^2 and *Y* = interval between *X* and Y in years.

6.2.2.2 Land use classification

There are two land use classification process methods, namely supervised classification and unsupervised classification techniques. In supervised classification process, spectral signatures are developed from a priori identified locations in the image. These specified locations are given the generic name (e.g., 'forest') and are defined by the user. In general a vector layer is digitized over the raster scene. This vector layer will consist of different polygons overlaying on different land use types (Rai, et al., 2011; Jensen & Lulla 1987; Jensen, 2004).

The unsupervised classification techniques, on the other hand, do not require the user to identify any information about the features enclosed in the images; the user identifies which bands of Land-sat-5 TM image should be used to create the classifications, and determine the number of classes to categorize the land cover features. The method of classification of land use in this study was done based on a method by Anderson identifying residential land, water bodies, agricultural land, bare land and forest land (Anderson *et al*., 1976). Following the image classification from each year, change detection algorisms of post classification were used to determine changes in land cover for three periods: 1986-1999, 1999-2011 and 1986-2011. This approach was also followed by Jensen, (2004) to monitor land use changes in Atlanta, Georgia.

In this study the unsupervised image classification method was employed in parallel with Google-Earth map for identifying the actual feature and to evaluate the ground truth observation. In order to create a sample set, a set of test points was randomly selected. The tools mentioned above were used to identify the rate of change of land use and, for image classification, ENVI 4.2 and Arc-Map10.2 software were employed. The final out puts were maps at 1: 150,000 scale of land use changes and Normalized Differencing Vegetation Index (NDVI).

Table 6.1: Land use and, or cover classes used in this study.

Classes	**Definition**
Urban and, or built up areas	Residential, industrial and commercial complexes, transportation and road networks, communication and utilities.
Water	All areas of streams and reservoirs
Bare land	Areas of soil, sand, or rock, almost without vegetation.
Agriculture & Tree Vegetation	Trees, grassland, shrubs, crop fields and cultivated lands

Forest Land	Deciduous, evergreen and mixed forests (natural and manmade forests).

6.2.2.3 Analysis of Vegetation Change

Urban vegetation cover reduces climate change by reducing the temperature of urban areas (Makhelouf, 2009; Bottya¨n *et al.*, 2005). Hence monitoring of vegetation cover is vital despite requiring synoptic and representative coverage of satellite imagery (Bikneh, 2007). In doing the assessment, the Normalized Differencing Vegetation Index (NDVI) method is used as the most ordinary ratio indices of vegetation. The NDVI is empirical formula intended to stress the spectral difference between the red (Band-3) and near infrared (Band-4) regions of spectrum of electromagnetic waves. NDVI varies between zero and one. The closer NDVI is to one the more the vegetation is active photo-synthetically (Jenson 2004). NDVI is evaluated as:

$$NDVI = (NIR - RED)/(NIR + RED) \qquad \text{Eq. (6.2)}$$

where NIR is near infrared band for a given pixel, RED is the red band response. Atmospheric adjustment methods credit for one or more of the twist effects of the atmosphere and thereby change the values of brightness of each pixel to reflectance's which is actual as they would have been calculated on the ground

6.2.2.4 Observed and Projected Urban Heat Island (UHI)

One of the major problems to be faced in the investigation of observed and future urban climate is the absence of a dense and long-term station network in a city. For this reason, data from only two stations (Addis Ababa observatory and Addis Ababa Bole International Air-port station) covering the period 1960 -2001 were analyzed.

a) Observed UHI

Minimum temperature data from Addis Ababa observatory (AAOBS) and Bole International Airport (AABIA) stations are used for UHI assessment. The population density of Bole sub-city is about 2,753 and the corresponding density of OBS station area is about 23,900 inhabitants per square kilometer. AAOBS serves as the urban reference station in the calculation of UHI, whilst Station AABIA serves as rural station. Addis Ababa UHI is then defined as:

$$\Delta T_{u-r} = T_{min}AAOBS - T_{min}AABIA \qquad \text{Eq. (6.3)}$$

where, $\Delta T_{u-r}$is urban heat island intensity (UHI) and $T_{min}OBS$ and $T_{min}\,BOL$ are the daily minimum temperature at the station Addis Ababa observatory (AAOBS) and Addis Ababa Bole Airport (AABIA), respectively.

b) Projection of UHI using Statistical Downscaling Model (SDSM)

Wilby (2008) used SDSM to predict future UHI for the city of London. The same method was applied for predicting UHI for Addis Ababa. A statistical variables relationship was developed in downscaling nocturnal urban heat island. The variables are daily minimum temperature difference between the Addis Ababa Bole rural site and that of Addis Ababa observatory urban site. The predictors of large scale indices were obtained from the reanalysis of data from the National Centre for Environmental Prediction (NCEP) (Wilby *et al*., 2002).

The predictand UHI intensity $\Delta T_{u-r}$is given as:

$$\Delta T_{u-r} = aX + p \qquad \text{Eq. (6.4)}$$

where, *aX* is a Predictor of minimum temperature variable and *p* is correlation values.

6.3 Results and Discussions

6.3.1 Land Cover Change

The land cover pattern of the city has to be assessed before dealing with the temporal and spatial climate results of the city, Fig 6.1 shows the land cover classification agriculture and grass land, built-up, forest and bare-land for the three Land-sat images of 1986, 1999 and 2011. During the year 1986, the city’s land use and land cover was dominated by forest cover in the Northern and Northwestern part, while agricultural and grasslands dominated the Southern and Southeastern parts. The built-up area was concentrated in the central part of the city. The 1999 and 2011land cover maps show an expansion of built-up areas, shrinkage in the forest and agricultural lands in all direction of the city.

The land cover changes that occurred due to land use change during the period under consideration is summarized in Table 6.2. Water bodies were not detected in the analysis. However, meandering forest corridors are noticed and the rivers of the city are associated with these network .About 43 %, 32 % and 11 % of the total area were under forest cover in 1986, 1999 and 2011, respectively. The bare land covers about 7.7 %, 13.04 % and 21.9 % of the total geographical area of the city in 1986, 1999 and 2011, respectively. About 32 %, 33 % and 27 % of the area was agricultural, grass or vegetation land in 1986, 1999 and 2011, respectively. About 17 %, 22 % and 40 % area was under built-up in 1986, 1999 and 2011, respectively. In general, the remote sensing satellite data and the results of the geographic information system (GIS) analysis have shown built-up areas have increased by121.88 km^2 within 25 years.

Table 6.2: Summary of Land-sat classification area statistics for 1986, 1999 and 2011.

Land cover class	1986		1999		2011	
	Area (Km^2)	%	Area (Km^2)	%	Area (Km^2)	%
Forest	225	43	166	32	55	11
Urban/ Built-up	87	17	114	22	209	40
Agriculture & grass/vegetation	167	32	171	33	141	27
Bare land	40	8	68	13	114	22
Sum total	519	100	519	100	519	100

6.3.1.1 The annual percent of change of land use and land cover

The rate of change for forest lands was negative, which implies a decline in areal coverage, whereas settlements and degraded land increased their areal extent at the expense of the forest and agricultural lands. Over the study period, the extent of built-up areas has increased by 4.8 km^2 per year against 76 % decrease of forest cover and 61 % decrease of agricultural land areas. Bare-land has increased mainly because of large-scale extraction of construction materials.

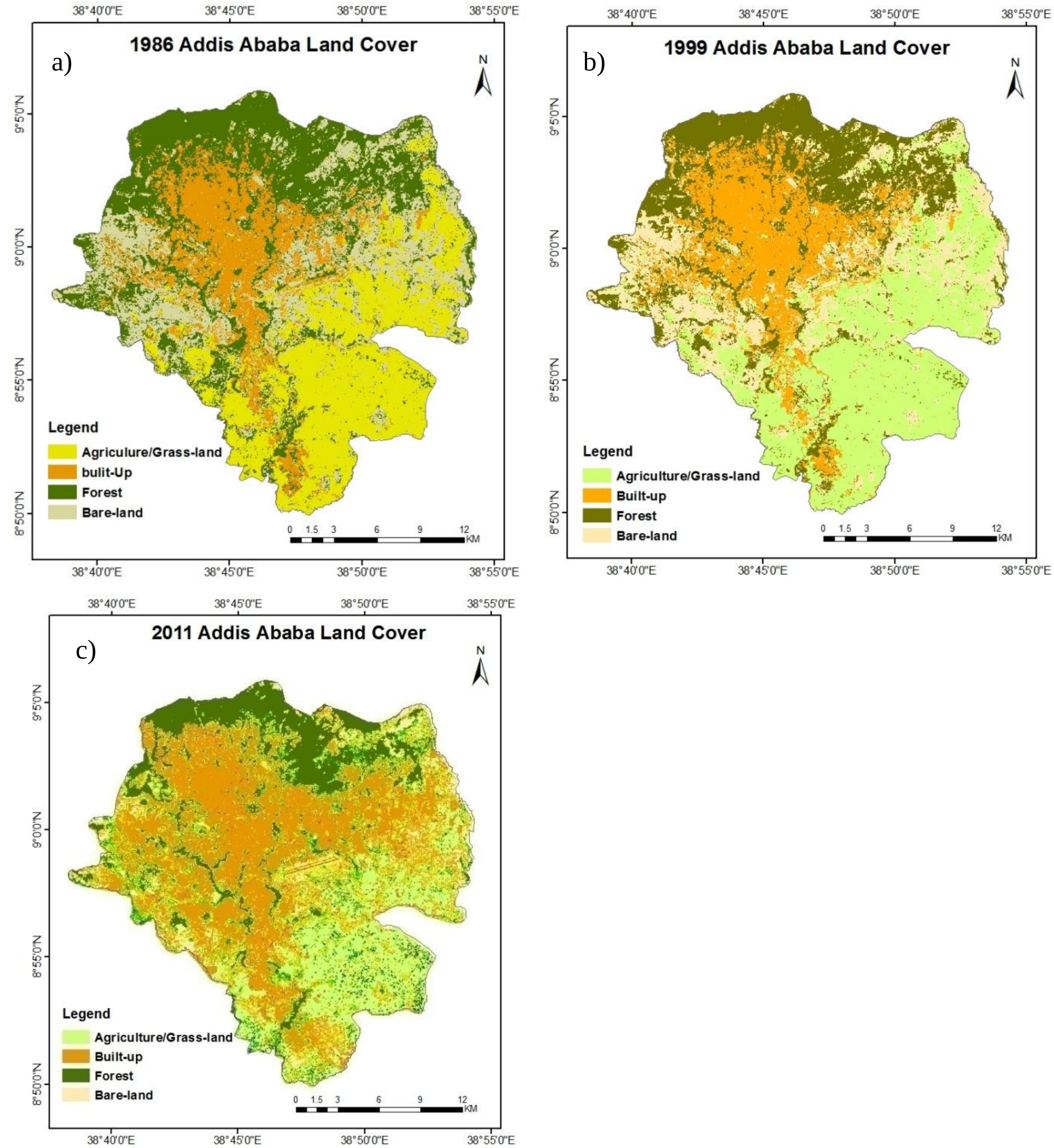


Figure 6.1: Addis Ababa Land use/Land covers a) 1986, b) 1999 and c) 2011.

Areal statistics in Table 6.3 shows the amount of land in km^2 converted to or gained from other categories of land use. For instance, 1.03 square kilometers of agricultural and tree cover land

and 6.81 square kilometers of forest lands of 1986 were transformed to built-up land. Thus, built-up cover of 2011 gained 4.88 square kilometers of land.

Table 6. 3: Land cover rate of change in Addis Ababa (km^2) (1986 to 2011).

	1986-1999		1999-2011		1986-2011	
	Area		Area		Area	
	Km^2	%	Km^2	%	Km^2	%
Forest	-4.55	-0.84	-9.25	-1.75	-6.81	-1.28
Built-up	2.05	0.38	7.93	1.5	4.88	0.92
Agriculture& Tree/Grass	0.36	0.07	-2.53	-0.5	-1.03	-0.2
Bare land	2.13	0.38	3.85	0.75	2.96	0.56

6.3.1.2 Vegetation Change

General assessment of vegetation cover change could be assessed using NDVI values, which allow making comparisons between different dates of imaging; NDVI implicitly shows the overall change in vegetation cover of a given place. The results of NDVI for two different years (images taken on January 25, 1999 and January 10. 2011) were used to detect changes in vegetation cover. The original images of Land-sat images of Band 3 (RED) and Band 4 (NER-INFRARED) for NDVI were atmospherically corrected for final NDVI images.

Table 6.4: NDVI values before and after Atmospheric Correction.

Land Cover	NDVI-Before correction	NDVI-After correction
Forest	0.276	0.389
Urban	-0.333	-0.239
Agriculture and vegetation	-0.15	-0.05
Bare land	-0.246	-0.146

The outcome in Table 6.4 shows that the NDVI of the original values is less than the surface reflectance. This eliminates the negative effects of gaseous observation, molecular scattering and aerosols improving the quality of the images. Vermote et al., (1997) identified that the NDVI values, on average, increased from -0.33 to 0.38 after atmospheric correction and also indicated that bare-land values are less than 0.5 and dense vegetation is greater than 0.75. The NDVI density of vegetation showed a radical decrease from 0.82 in1999 to 0.66 in 2011; this shows how the degradation of vegetation cover increased from time to time (see Table 6.5 and Figure 6.2). The major change in vegetation cover occurred in the central and eastern parts of Addis Ababa.

Table 6.5: NDVI differences (1999 and 2011).

Pixel Statistics	1999	2011
Maximum	0.82	0.82
Minimum	-0.50	-0.50

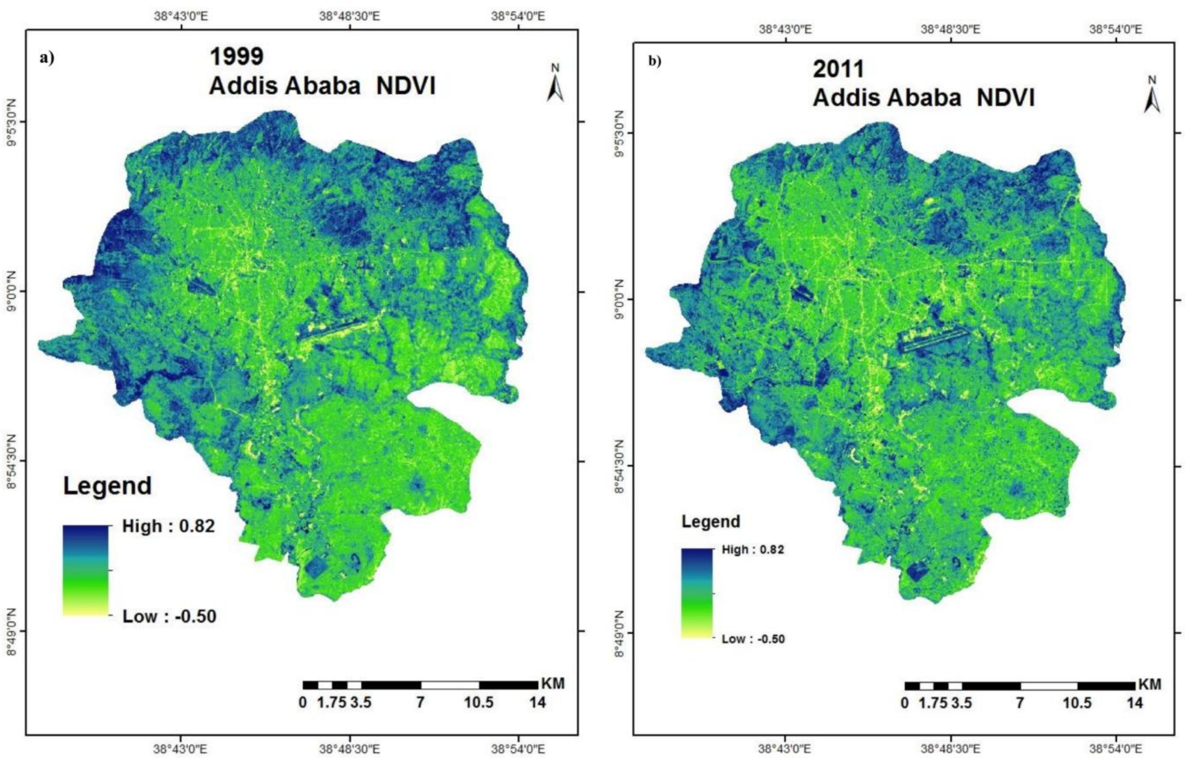


Figure 6.2: NDVI Images for the city of Addis Ababa for the two periods (1999 &2011).

Note: Bare Land: < 0.5 & Dense Vegetation: > 0.75 (Source: Vermote *et al*., 1997).

6.3.2 Population Distribution in Addis Ababa

The demographic, social and policy issues are among the major causes for land-cover changes of a given area (Carlson and Arthur, 2000). During the previous century, Addis Ababa's population had exhibited substantial increase. The city has been undergoing rapid rate of urbanization triggered by rural-urban migration and socio-economic development. The city's population had tripled between 1961 and 1984 and almost doubled between 1984 and 2008. Such an increment rise in population requires additional space for settlement and construction of auxiliary services and infrastructure. In the year 2000 the population was 2,112,737, while the population was projected to be 2,980,001 for 2011. The average population density of the city is about 5,654 persons per kilometer square, which shows an increase of 1,624 person / km^2 between 2000 and 2011 (CSA, 2011).

The population distribution in the city shows that the highest percentage, 15.7 % or 466,539, of the city's population live in Kolfe Keranyo sub-city (west), occupying an area of 61.25 sq km (Table 6.6). It is followed by Yeka sub-city (east) that accounts for 12.7 % or 377,091 of the city's population and occupying an area of 85.98 sq km. The third largest sub city is Nefas silk Lafto (south west) with 11.5 % or 344,043 of the city's residents living in an area of 68.30 sq km. Population size by density of sub cities is indicated in Table 6.6.

High population density was observed in the central parts of the city including Addis-Ketema, Arada, Kirkos and Lideta (16,000-23,900 persons / km^2) and in contrast with that of Bole, Yeka, Nifas Silk Lafto and Akaki sub-cities (1,669.9 - 5,037.2 person / km^2).

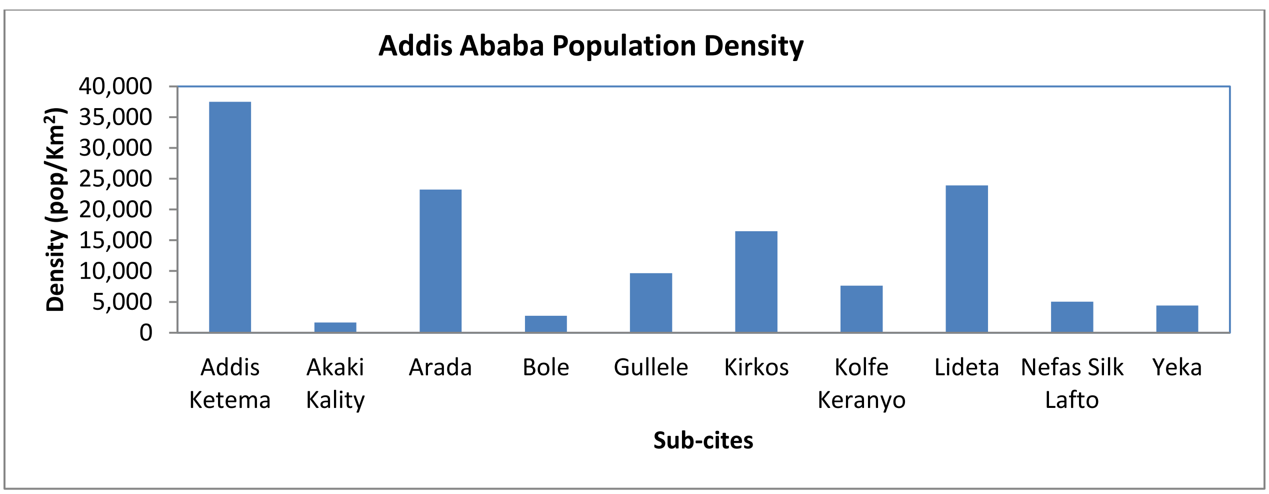


Figure 6.3: Addis Ababa Population Density.

Table 6.6: Population size of the 10 sub-cities in Addis Ababa by area and density (CSA, 2011).

Sub-City (Name)	Total Population (n)	Area (km^2)	Density (pop/Km2)
Addis Ketema	277,786	7.41	37,488
Akaki Kality	197,180	118.08	1,669.90
Arada	230,065	9.91	23,215.40
Bole	336,115	122.08	2,753.20
Gullele	291,113	30.18	9,645.90
Kirkos	240,651	14.62	16,460.40
Kolfe Keranyo	466,539	61.25	7,617.00
Lideta	219,418	9.18	23,901.70
Nefs Silk Lafto	344,043	68.3	5,037.20
Yeka	377,091	85.98	4,385.80
Total (Addis Ababa)	2,980,001	526.99	5,654.8

6.3.3 Urban Heat Island (UHI)

The analyses made on the time-series data on daily nocturnal urban heat island (UHI) for the selected coldest period of 1967-1968 showed that, the warmest days in the city center was in November which was warmer by about (+6.0 ºC) than Bole Airport site, whilst the coldest day was in April which was colder by about (-5.8 ºC) than Bole Airport site (Fig. 6.4a). The urban warming was high during the dry season from October to January and low during the wet season from June to September (Fig. 6.4b).

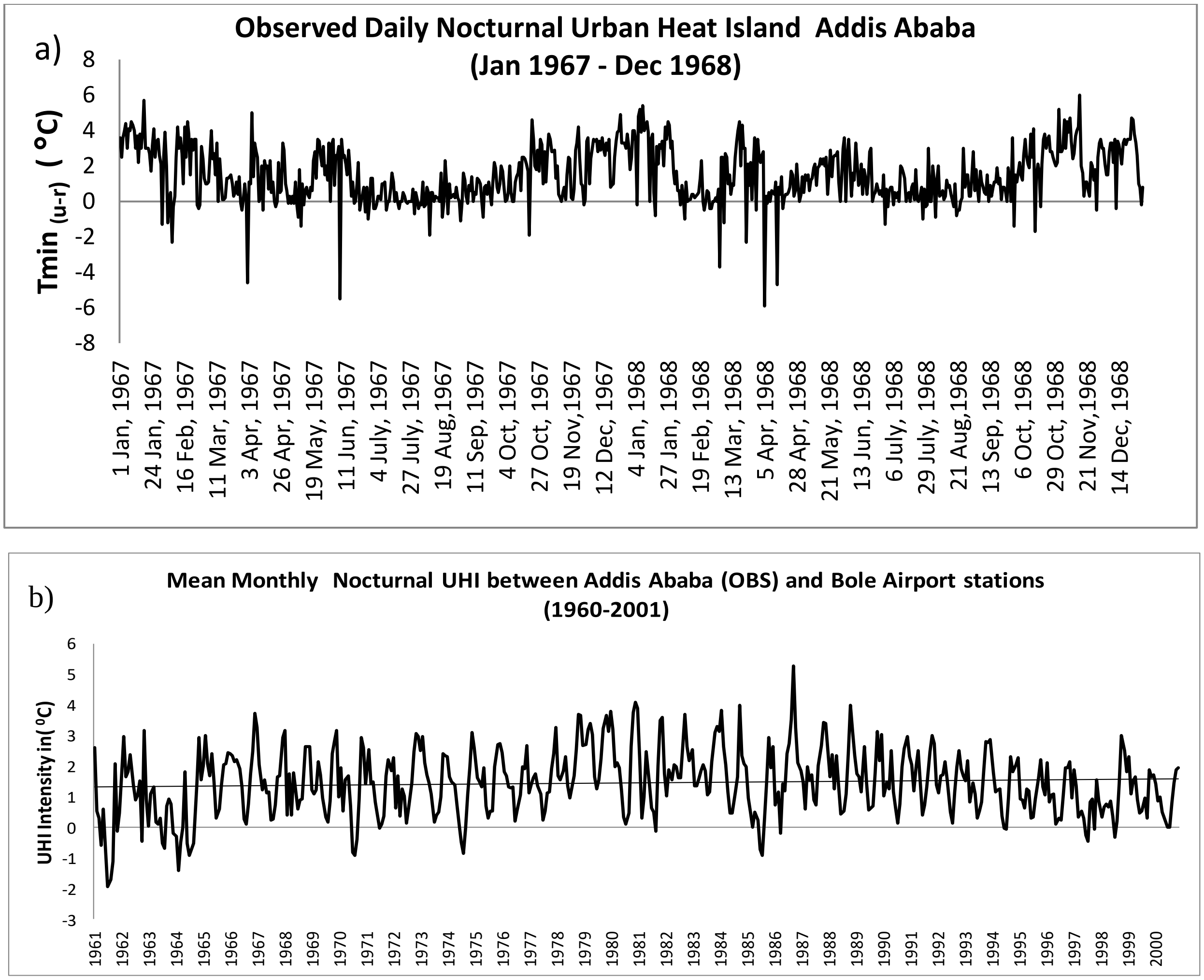
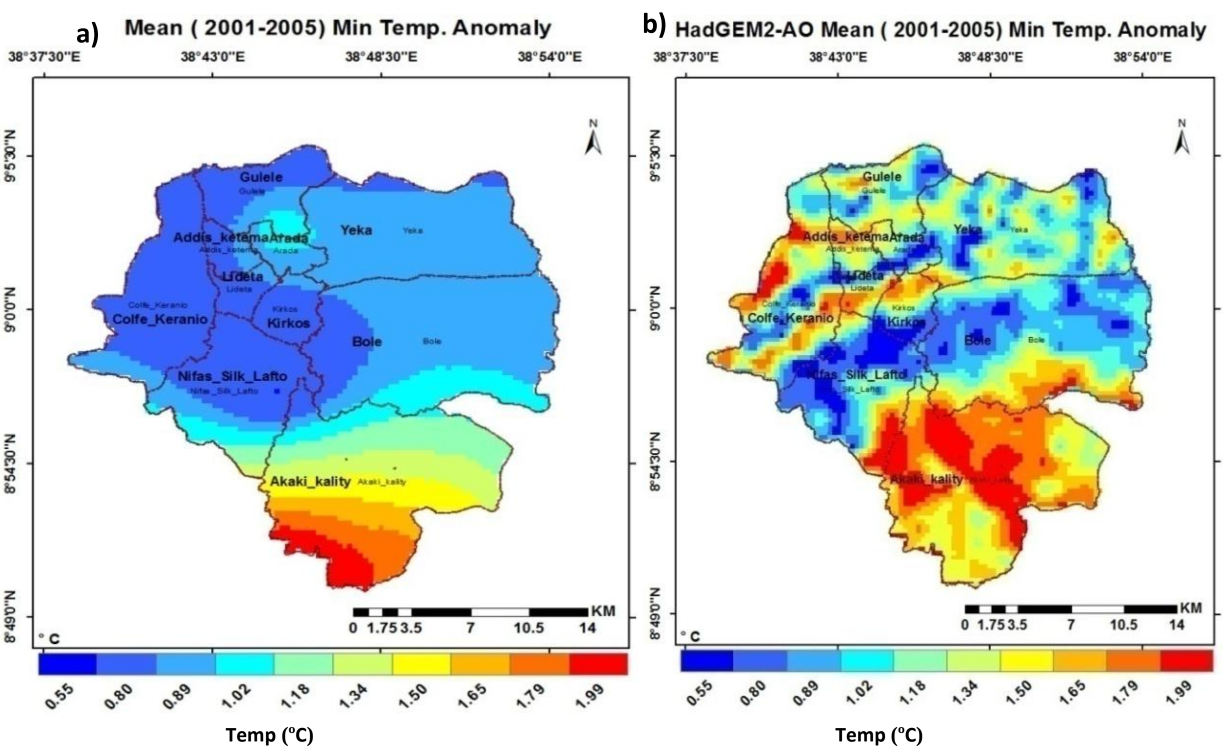


Figure 6.4: Mean Daily nocturnal UHI intensity for the coldest period (January 1967 to December 1968) (a) and Mean Monthly Nocturnal UHI for the period (1960-2001) (b) which is the difference of minimum temperature between Addis Ababa OBS and Bole International Airport.

6.3.4 Climate and Urbanization

Long term mean (1981-2010) of annual maximum and minimum temperature maps are reconstructed from gridded observation and HadGEM2-AO climate model using Arc-Map 10.2 (Fig. 6.5a-f). The change in the mean annual minimum and maximum temperature and rainfall for 2001-2005 is evaluated with respect to the 1981-2000 average. The comparison of the climate data between observed grid and HadGEM2-AO climate model shows generally similar spatial patterns despite difference in the magnitude of the climate variables, with notable difference in rainfall (Fig. 6.5). The observed grid data is about 10km resolution and HadGEM2-AO is a very high resolution (1 km) data. This difference in resolution has somewhat contributed to the discrepancy between the two data sets as reflected in smoother spatial patterns in observations than in HadGEM2-AO.

The minimum temperatures increases from 1.02 to 1.99 ºC in the sub-city of Arada, Addis Ketema, Kirkos, southern Gulele, Yeka and Bole) to the southern low-lying sub- city of Akaki Kality (Fig. 6.5a-b). The maximum temperature change also increases from (-0.32 to 1.3 °C) (see Fig. 6.5c-d). The highest increase of maximum temperature is in the Yeka and Akaki sub-cities(up to 1.3 ºC) (Fig. 6.5c-d). The HadGEM2-AO and observed grid mean rainfall change shows increasing range from 12 to 95 mm. The rainfall gradient increases from north-east part of the city to southern part of the city (Fig. 6.5 e-f).



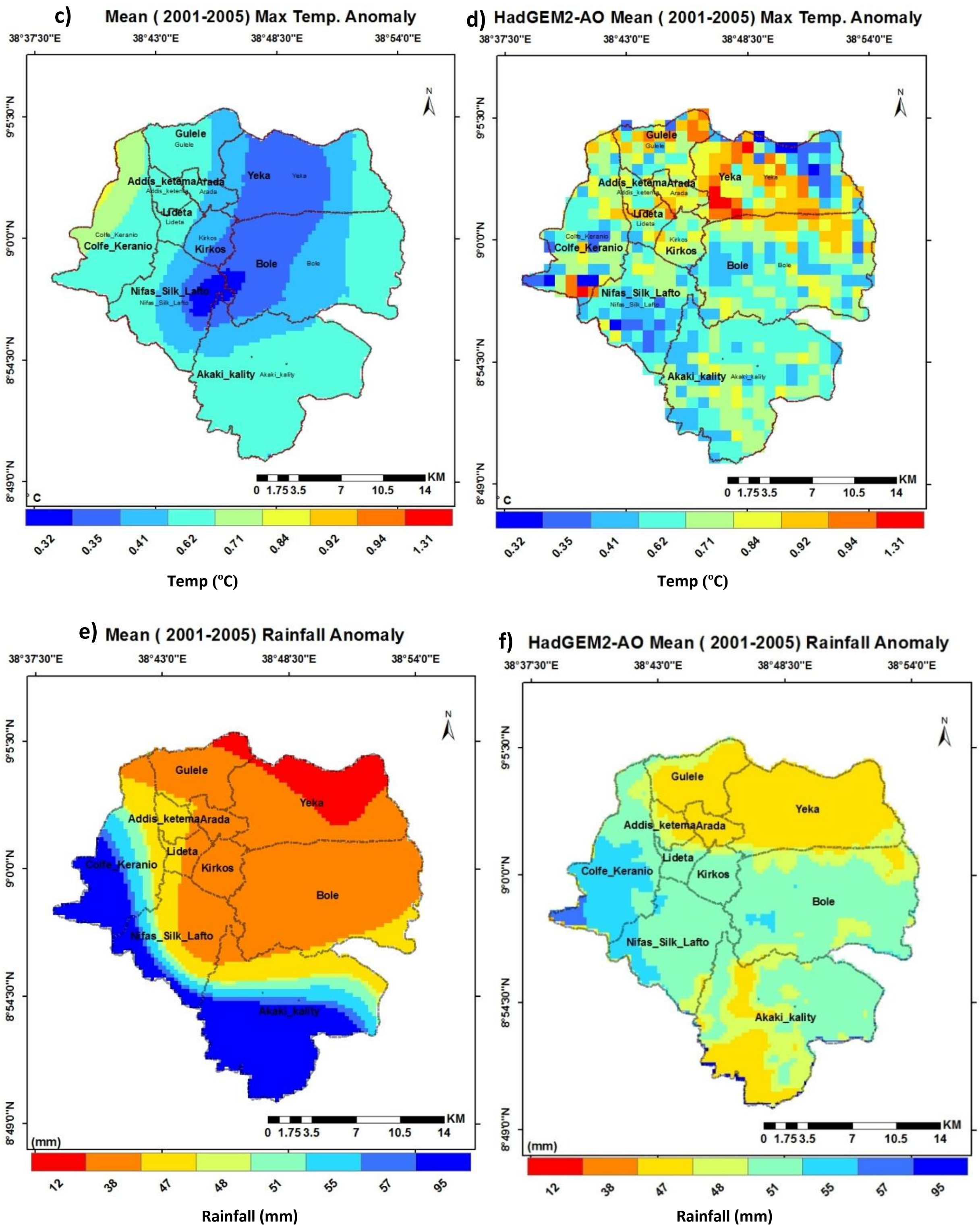
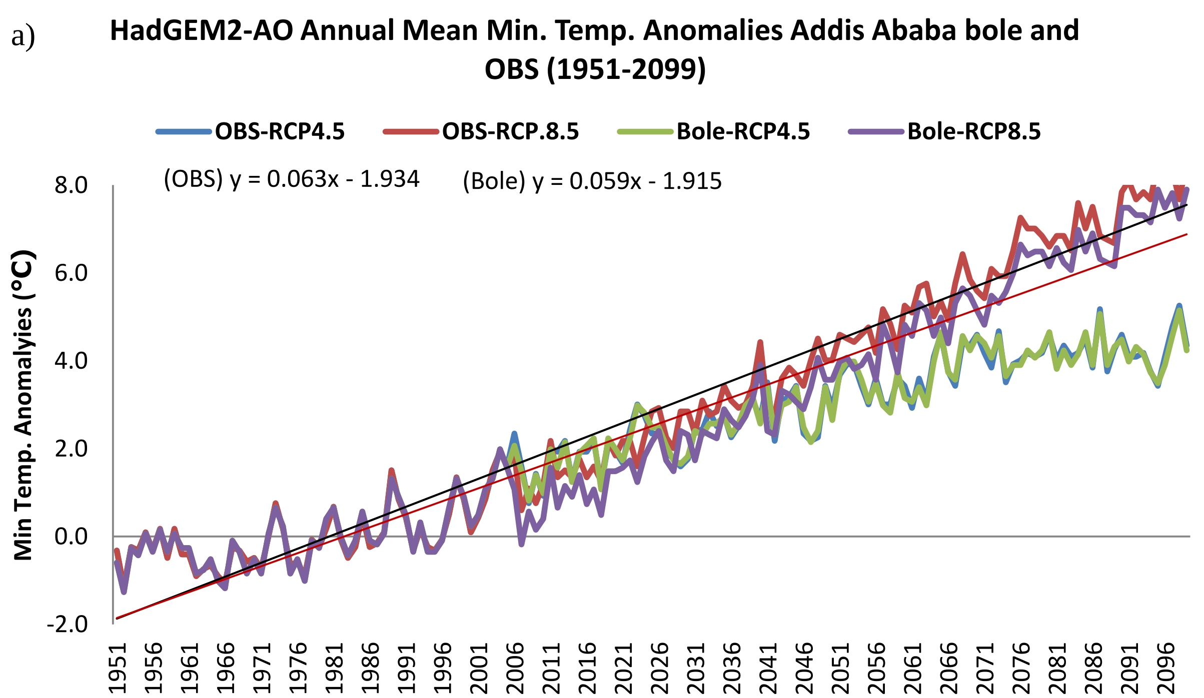


Figure 6.5: Addis Ababa (2001-2005) observed grid and HadGEM2-AO Anomalies (a-b) mean annual minimum; (c-d) maximum temperature; (e-f) rainfall from the mean (1981-2000).

HadGEM2-AO projected temperature for Addis Ababa City under RCP4.5 and RCP8.5 scenario for the period 1951 to 2099 is presented in Fig. 6.6. Significant warming of minimum temperatures under RCP8.5 scenario at Addis Ababa Observatory and Bole Airport station will be expected in the period between 2063 to 2099, but the warming in the inner parts of the city (i.e., Addis Ababa Observatory station) will be higher than that at the rural station (i.e., Addis Ababa Bole International Airport) for both minimum and maximum temperatures. The projected future Addis Ababa Observatory (AAOBS) mean surface-minimum temperature expected to increase for the period 2071 to 2099 from 4.6 to 5.3 °C for RCP 4.5 and from 6.4 to 8.5 °C for RCP 8.5 with respect the base period (1951-2000) mean. The increase in the minimum temperature in RCP8.5 scenarios will be larger than that of the maximum temperature, and the trend in minimum temperature change for Addis Ababa Observatory (AAOBS) and Bole International Airport stations is 0.63 °C and 0.59 °C per decade, respectively (Fig. 6.6a). The warming trend in maximum temperature under RCP8.5 scenario (Fig. 6.6b) for Addis Ababa Observatory station and Addis Ababa Bole Airport Station is 0.42 °C and 0.39 °C per decade, respectively.

a)



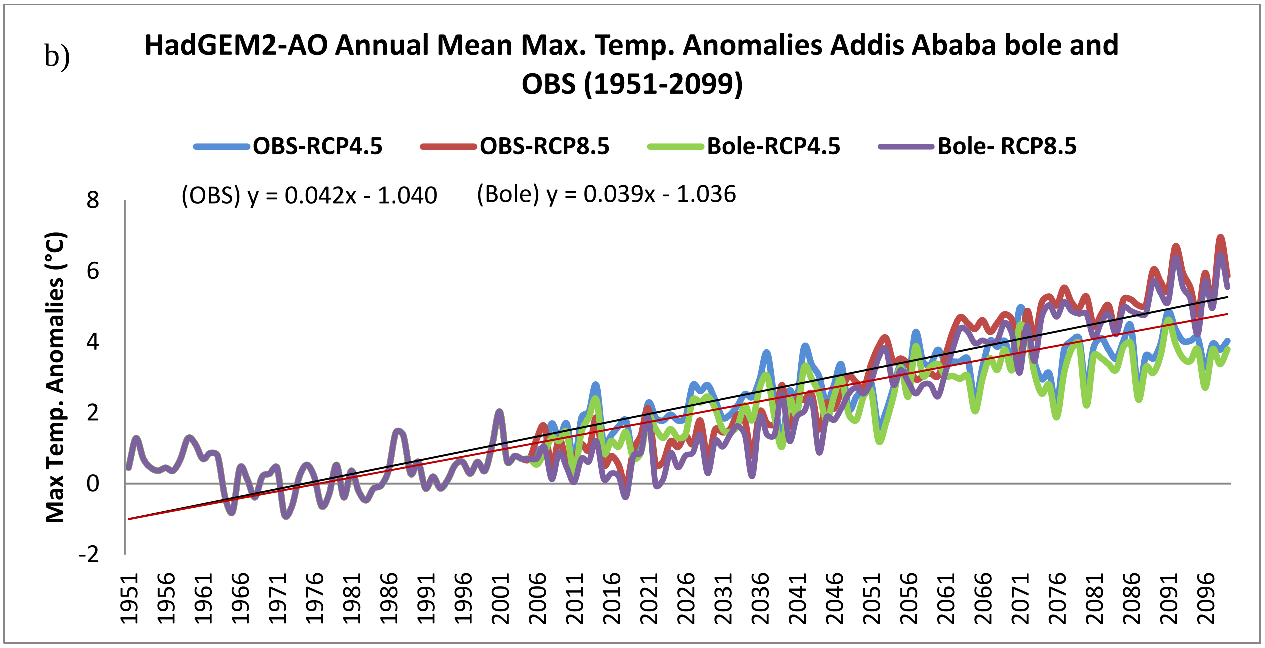


Figure 6.6: Addis Ababa Bole and OBS annual mean a) minimumand b) maximum temperature anomalies (compared to 1951–2000 mean) for the period 1951–2099.

6.3.5 Temperature Change and Population Density

Fig. 6.7 shows the scattered diagram of minimum and maximum temperature change with population density. The line indicates the quadratic fit to the data. Results from the fitting shows that population density considerably influences the minimum temperature change as reflected by strong correlation (R^2=0.93). Since higher population density requires higher building density and, therefore, results in enhanced radiation trapping and high thermal inertia (Steeneveld, et al., 2011). Also anthropogenic emissions enhanced in densely populated areas. The strong correlation of UHI with population density as indicated in this analysis confirms earlier findings from Oke (1987) and this builds our confidence in the grid observation data. However, the mean annual maximum temperature change had weak relation with population density (see Fig. 6.6b).

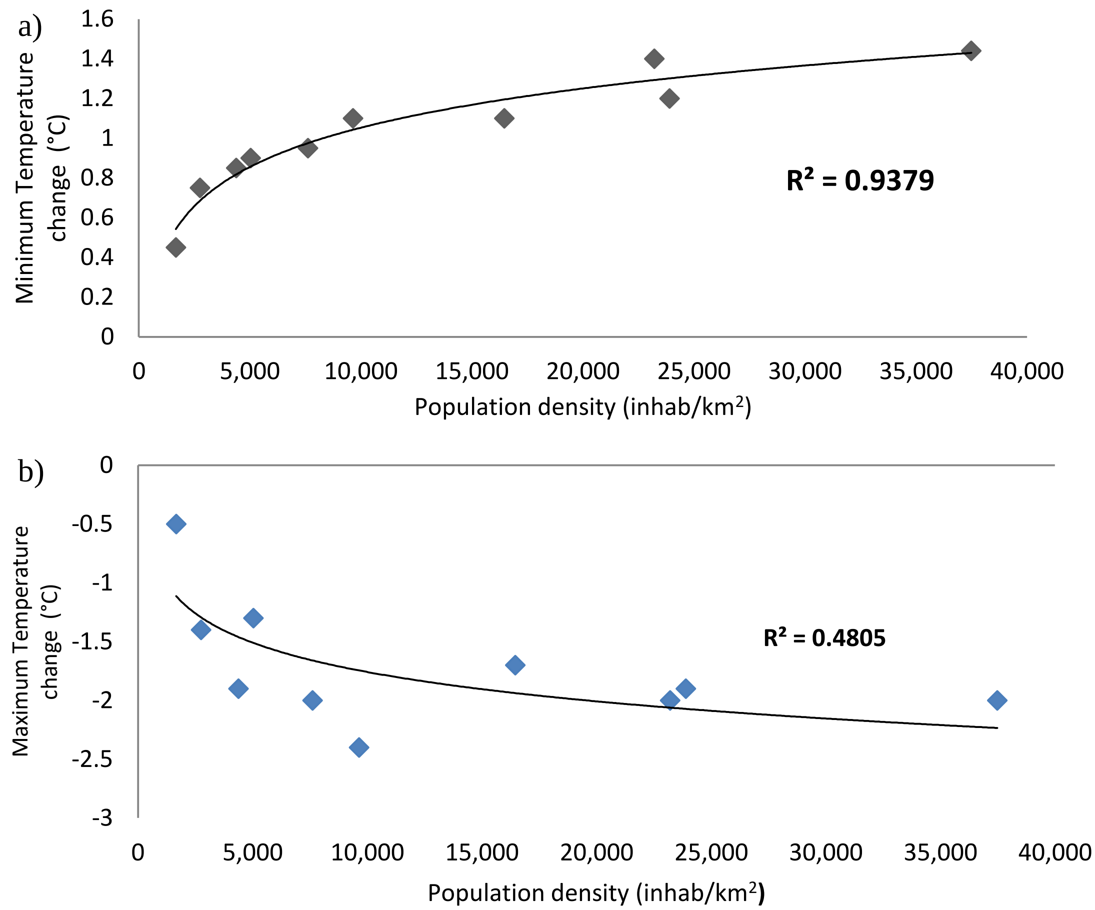


Figure 6.7: Scatter diagrams of (a) minimum temperature change, (b) maximum temperature change with population density data for at ten sub-cities in Addis Ababa. Lines indicate the fitting to the data.

6.3.6 Projected change in Nocturnal UHI under emission scenarios A2 and B2

The study indentified major predictor and predictand relationships for UHI using ΔT_{u-r} Eq. (6.3). The SDSM model was calibrated using the difference of daily minimum temperatures (Bole Airport and OBS stations) of 1961 to 2000 and the reanalysis of the National Centre for Environmental Prediction (NCEP) climate variables centered on the nearest grid location in the study area (Y= 31 and X= 11 or Latitude: 9.01 °N and Longitude: 38.74 °E) to downscale UHI as per Eq. (6.4). The predictors of large scale indices are obtained from the outputs of the GCM of HadCM3 model scenarios of A2 and B2 in the manner described in Chapter 3.

Table 6.7: Atmospheric predictor for UHI.

Partial correlation with Minimum Temperature (1961-2001).			
Pridictand	Predictor (X)		p
Nocturnal UHI	Ncepmslpaf.dat	Mean sea level pressure	0.000
1961 - 2000	Ncepp5_faf.dat	500 hpa airflow strength	0.0012
ΔT_{u-r}	Ncepp500af.dat	500 hPa geopotential height	0.000
	Ncepp8_faf.dat	850 hPa airflow strength	0.0001
	Ncepp8_vaf.dat	850 hPa meridional velocity	0.0013

To develop a statistical model five variables, as shown in Table 6.7, were screened and the analysis shows that the mean sea level pressure, 500 hPa airflow strength, 500 hPa geopotential height, 850 hPa airflow strength and 850 hPa meridional velocity or wind are more influencing the UHI. The pressure is related to cloud cover, and, high cloud cover with low pressure system reducing UHI (Morris et al., 2001; Schlunzen et al., 2010). The variables exhibit high correlation values, with p-values less than 0.005, implying that predictor-predictand relationship is statistically significant.

Fig. 6.8 shows mean climatology of Nocturnal UHI comparisons between observed and National Centre for Environmental Prediction (NCEP) reanalysis data with respect to the 1961-2000 base periods. The agreements between the UHI from the two data sets is extremely good. However, this is expected as the reanalysis is partly measurement and partly model.

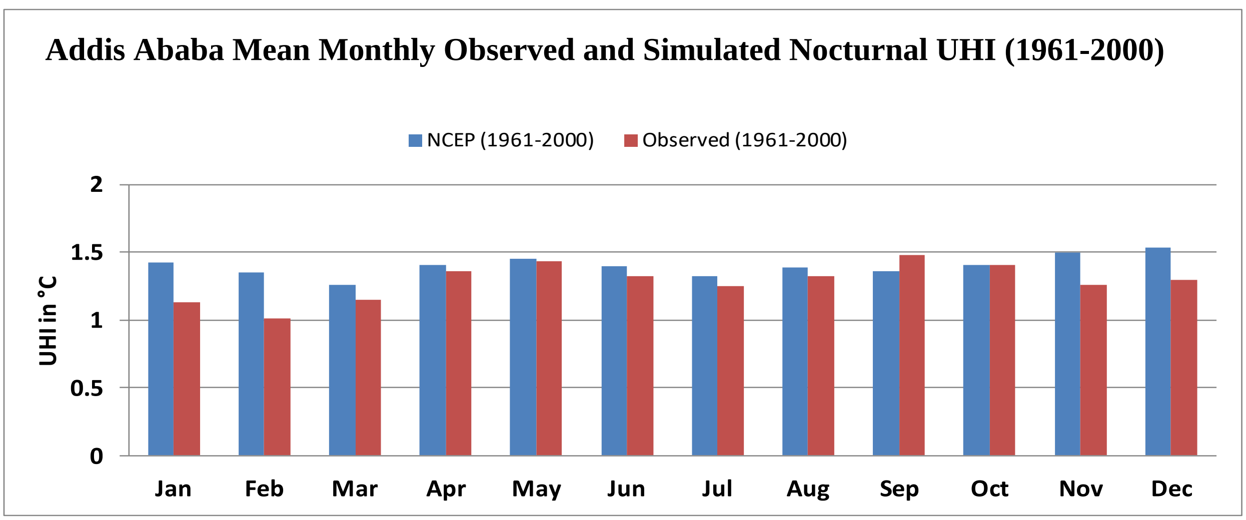
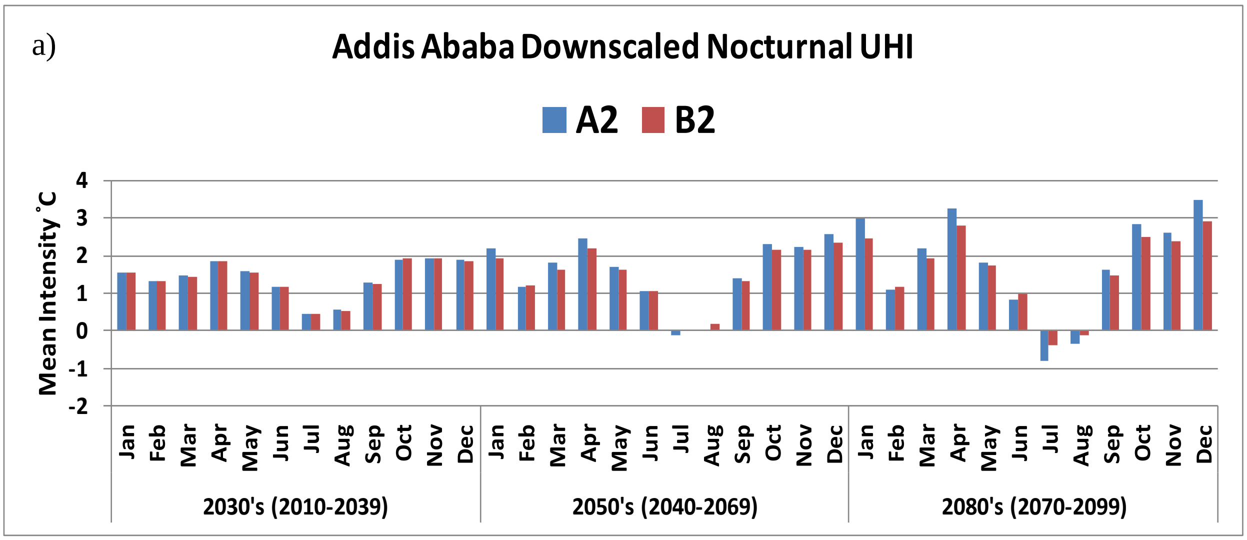


Figure 6.8: Addis Ababa Observed and Downscaled Nocturnal UHI.

Changes in Nocturnal UHI show an increase of night time temperature during the dry seasons of October to January in all projected periods (2030s, 2050s and 2080s), whereas, during June to September, the rural site is warmer than the inner city (See Figure 6.9a). Under A2 scenario the highest urban warming will occur in the period from October to December (2.5 ºC and 3.2 ºC) during the 2050s and 2080s. Interestingly, weakening of the mean UHI intensity occurs in summer (the Kiremt or the long rainy season).



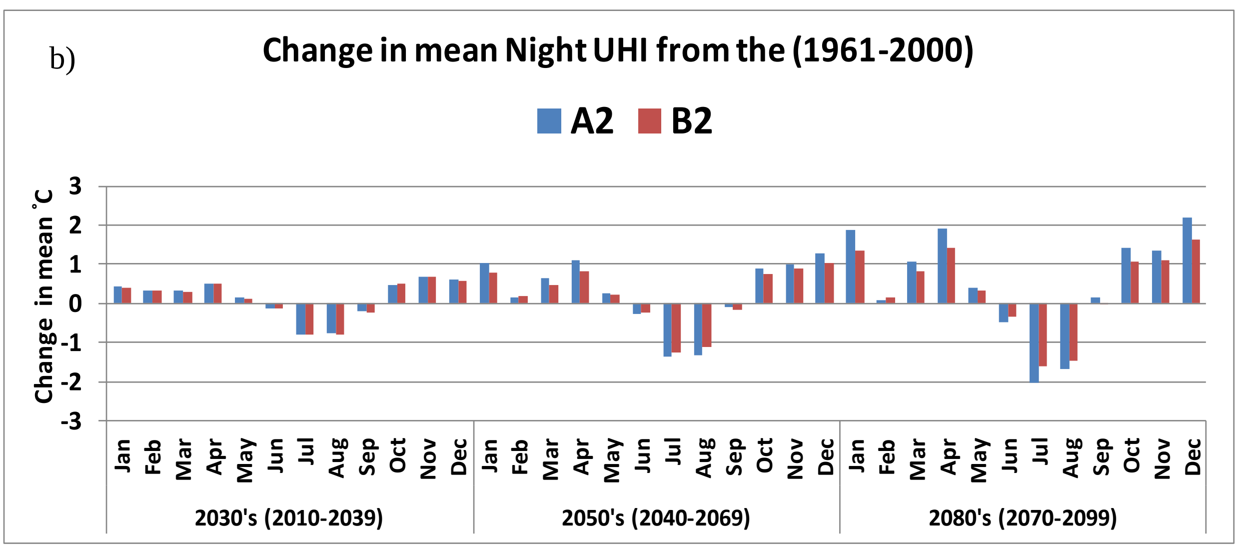


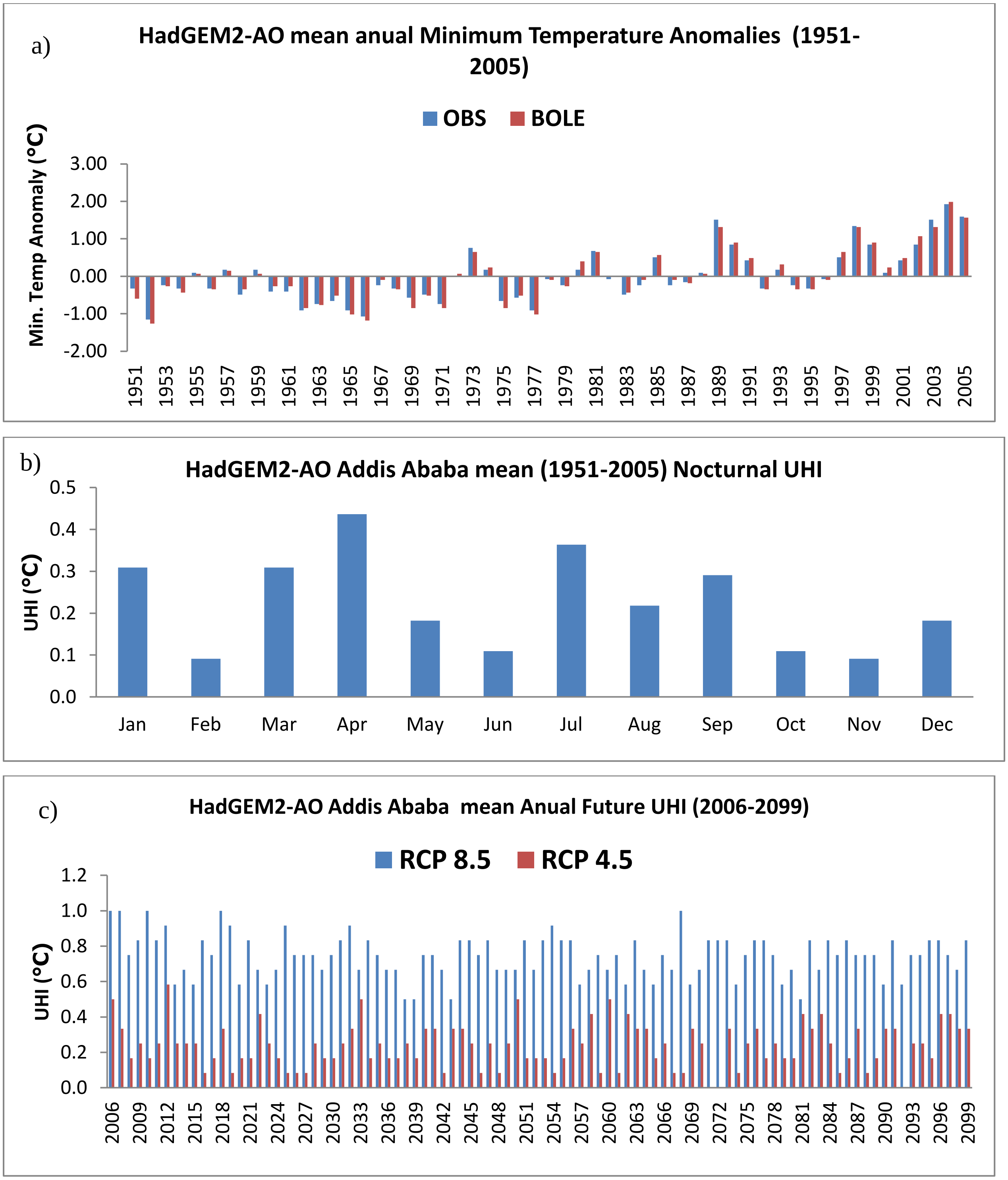
Figure 6.9 a) monthly mean nocturnal UHI; (b) change from the mean UHI of (1961-2000).

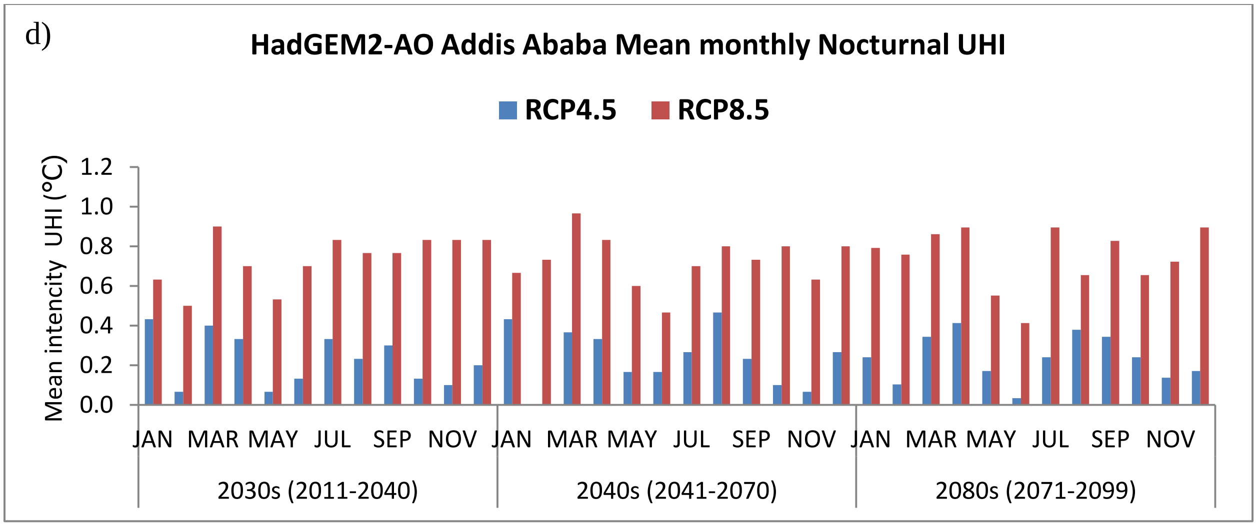
Both A2 and B2 scenarios suggest more intense UHI events to occur in the period from October to December. The mean nocturnal UHI change also shows increases in Addis Ababa's nocturnal UHI and a high occurrence of intense heat island incidences during winter (see Fig.6.9b). These changes are expected to be more persistent and intense during drought periods. Because downscaling makes an immediate connection between synoptic circumstances and the UHI, compounding effects from drought time are misjudged in the present analysis. Though, even a conventional outlook supports the view that there will be an increase in higher intensity of UHIs. (Wilby, 2008)

6.3.7 Projected change in Nocturnal UHI under RCP 4.5and RCP 8.5 scenarios.

Fig. 6.10 (a) shows minimum temperature anomalies of HadGEM2-AO for both Addis Ababa OBS and Bole Airport station for the period (1951-2005).In both stations mean surface-minimum temperature anomalies vary between 0.6 °C to 2.0 °C.

The mean monthly nocturnal urban heat island (UHI) of Bole Airport and OBS stations shows higher UHI in April and reaches 0.4 °C (See Fig.6.10b). The projected mean annual UHI will increase under RCP 4.5 and RCP 8.5 scenario (See Fig.6.10c). The projected mean annual future UHI under RCP 8.5 scenario will increase from 0.5 to 1°C. Whereas the RCP 4.5scenario also shows an increase by about 0.2 to 0.5 °C (see Fig.6.10 c-d). Changes in Nocturnal UHI show an increase of nighttime temperature during the dry seasons of March, July, October to December in all projected periods (2030s, 2050s and 2080s). The highest urban warming will occur in the period from October to December (0.5 ºC and 0.7 ºC) during the 2030s, 2050s and 2080s. In both RCP4.5 and RCP8.5 scenario, weakening of the mean UHI intensity occurs in July (see Fig. 6.10e).


a)
HadGEM2-AO mean anual Minimum Temperature Anomalies (1951-2005)
OBS
BOLE
Min. Temp Anomaly (°C)
b)
HadGEM2-AO Addis Ababa mean (1951-2005) Nocturnal UHI
UHI (°C)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
c)
HadGEM2-AO Addis Ababa mean Anual Future UHI (2006-2099)
RCP 8.5
RCP 4.5
UHI (°C)



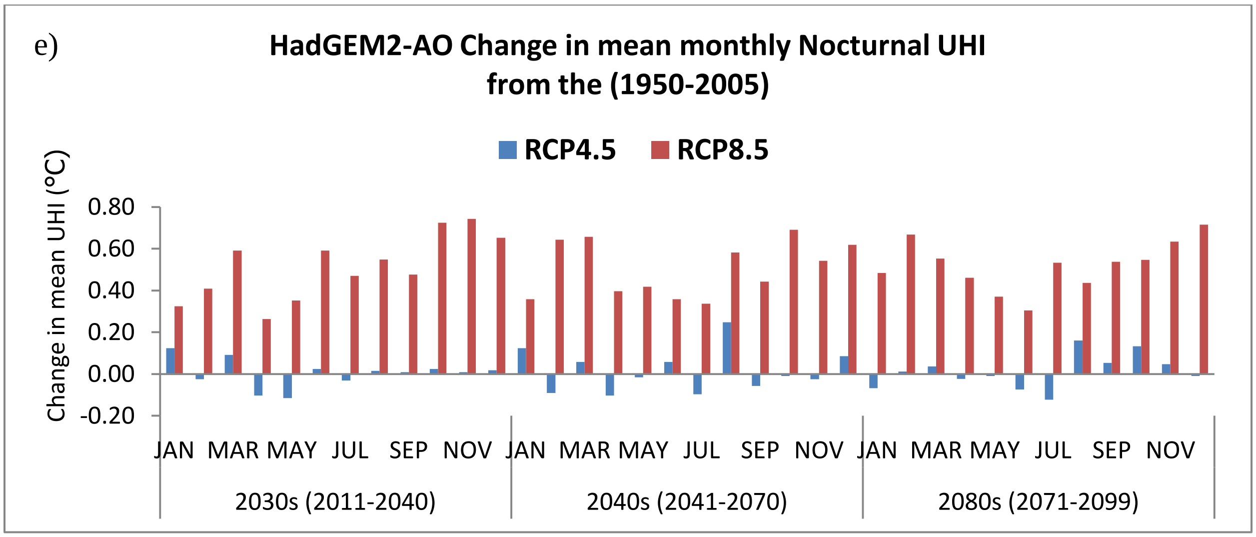


Figure 6.10 a)Minimum Temperature Anomaly (1951-2005), b) Sesonal Nocturnal UHI (1951-2005), c) Mean monthly minmum temperature trend (2006-2099), d) monthly nocturnal UHI e) change in Nocturnal UHI on RCP4.5 and RCP8.5.

6.4 Conclusion

This chapter examined temporal changes in land-use and land cover in Addis Ababa using Land-Sat data obtained for the years 1986, 1999 and 2011. This chapter also investigated the consequential modifications urbanization would make on the main climatological elements of the city within the general climate of a nocturnal temperature. The results indicated that built-up areas substantially expanded, while forest areas, vegetation covers and agricultural lands exhibited a sharp decline. As a result, the extent of bare lands had increased, mainly in the southern and eastern parts between forest areas and agricultural fields, especially in mountain and quarry areas.

The observed changes in land covers were largely attributed to urbanization, which also impact on the urban heat island effect. The minimum temperatures increases from 1.02 to 1.99 ºC in the sub-city like, Arada, Addis Ketema, Kirkos, southern Gulele, Yeka and Bole to the southern low-lying sub- city of Akaki Kality. The maximum temperature change also increases from (-0.32 to 1.31 °C).

The investigation made on Addis Ababa's projected nocturnal heat island shows that, the UHI will be intense in winter (dry seasons). By the 2050s and 2080s the change in mean nocturnal temperatures from October to December could be 2.5 ºC and 3.2 ºC, respectively. Also the mean annual future UHI under RCP 8.5 scenario will increase between 0.5 and 1 °C. The RCP 4.5 scenario shows an increase by about 0.2 to 0.5 °C.

This suggests the need for more urban greening by creating urban city parks and urban trees. The dry season has the highest frequency of hot conditions at both sites of Addis Ababa observatory station and Addis Ababa Bole Airport station, while the wet season recorded the lowest frequencies of hot condition. This indicates that the influence of urbanization on the climatic conditions (climatological elements) is much higher during the dry season. This has its own implications for thermal comfort planning and decision-making in the city. Higher frequencies of high temperatures observed in the city center suggest a heat stress and potential health risk. Hence measures that are capable of mitigating impacts of the increasing temperatures associated with the UHI are required in order to improve the city climate.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

The overall aim of this research was to create a body of knowledge on climate change and urbanization impacts on surface water supply together with adaptation measures for policy makers and scientific community. The study was conducted for the city of Addis Ababa focusing on the assessment of spatial and temporal observed climate and land use change; prediction of climate change and the Urban Heat Island (UHI) as well as water supply and demand of the city. The literature study provided an in-depth understanding of the interaction between the different levels of urbanization and climate at local, regional, Africa and global, contexts. The reviews also included intervention on the impacts of climate change on water supply and demand. The land use change impacts on urban climate were assessed by means of the urban heat island effect.

7.1 Assessment of present climate and future trends in climate over the city

Analysis of observations at the city center indicates the existence of identifiable variability in rainfall and changes in temperatures over time. The notable warm periods in the city of Addis Ababa in the 1990s and early 2000s, the dry periods of the 1970s and 1990s as well as above normal rainfall in 1982 and 1995 are definitively evident from the anomalies with respect to the selected baseline period.

The mean climatology of simulated rainfall, maximum and minimum temperatures obtained from WorldClim data center are in good agreement with the observed climatology at Addis Ababa Observatory for the same baseline period. The spatial variation in the mean climatology of the simulated variables is consistent with existing topographic features as revealed from observed distinct differences across north-south axis.

Two scenarios from the Special Report on Emission Scenarios (SRES) emission scenarios of (A2 and B2) and two from representative concentration pathways (RCP 4.5 and RCP 8.5) are considered to investigate potential future changes in climate variables at the city level in this study. The change in rainfall, maximum and minimum temperature over Addis Ababa city and its surrounding was determined for three selected future periods with respect to the baseline period that extends from 1950-2000 under the four scenarios. The finding of the study reveals that projected minimum temperature anomalies during 2030s with respect the above baseline period will be -1.4 °C and -0.9 °C in December under A2 and B2 scenarios respectively. During 2050s, the mean monthly minimum temperature anomaly is expected to be 1.3 °C in November and 1.5 °C in December under scenarios A2 and B2 respectively. During 2080s, it is likely to be warmer by 1.6 °C in November and 2.0 °C in December under A2 and B2 scenarios respectively. In general in both A2 and B2 scenarios an upward temperature trend is expected by the end of 21st century. The mean maximum temperature anomalies of the urban center at Addis Ababa Observatory station during 2030s will increase by 0.6 and 1.2 °C in December under A2 and B2 scenarios respectively. During 2080's the mean monthly maximum temperature anomalies shows a warming of 2.4 °C in November and 2.1 °C in December under A2 and B2 scenarios respectively.

On the other hand projected change under RCP 8.5 indicates anomalies of the mean monthly minimum temperature increasing by 2.9 °C and 3.2 °C in December during the 2030s under RCP 4.5 and RCP 8.5 scenarios respectively. Also during the 2050s the mean monthly minimum temperature anomalies shows an increase of 3.4 °C and 4.4 °C in December under RCP 4.5 and RCP 8.5 scenarios in this order. During the 2080s, the anomalies are expected to decrease by 4.1°C and 6.9 °C in December under RCP 4.5 and RCP 8.5 scenarios respectively.

The A2 and B2 scenario noted an overall increase in rainfall, however a decreasing trend is noted in the monthly precipitation particularly in major rainy season (e.g., June (43-45 mm) and August (22 mm)) during the 2030s and 2050s, and a decrease of up to 44 mm in June and 18mm in August in 2080’s while an upward trend in rainfall are expected in the month of September (up to 84 mm).Furthermore, the rainfall over Addis Ababa from the baseline mean during future periods shows a wetting trend generally under both representative concentration pathways. However, the rainfall anomalies are higher under RCP 8.5 than RCP 4.5 with significant difference during mid and end terms.

7.2 Investigation in water supply and demand

The water supply and demand is investigated using the WEAP hydrological model under different scenarios as the relational scenario between water supply-demand and population trends, climate change and unmet demand. The result revealed that the water availability for the projected future 5.5 million people will be insufficient in some sub-cities. The total demand of 2.5 % population growth would increase from 110 to 390 million m^3. The assumption is that the consumption per capita is anticipated to increase from 110 l/c/day in 2012 to 135 l/c/d by 2039. The water availability under low population growth scenario would result in insufficient amount of water supply in some sub-cities. As a result, the unmet demand is estimated at about 364.77 million m^3 in year 2039.

According to the WEAP model, in the case of high population growth rate (3.3 %) the population of the city will be 7 million people by the year 2039.The water availability under high population growth would cause much more insufficient water in some sub-cities. As a result the unmet demand is estimated at about 430.84 million m^3 in the year 2039 (Fig. 5.14), with the highest supply-demand gaps in Addis Ketema (75.64 million m^3), Mekanisa (65 million m^3) and Megenaga (34 million m^3).

The results of the WEAP model for the RCP 8.5 scenario combined with the low population growth scenario shows that the unmet water demand will be 372.87 million m^3 by 2039. On the other hand, the result of the RCP 4.5 and low population growth scenarios suggests a deficit of 168.13 million m^3 by 2039. The model’s result for the RCP 8.5 and high population growth (3.3%) scenario shows that the unmet demand will be 462.77 million m^3 by 2039. This indicates that the highest volume of unmet water demand is expected to occur under the high population growth and the dry climate years that will have big repercussions on water shortages in the city.

7.3 Assessment spatial and temporal urban land use and land cover change and its impact on climate for the city of Addis Ababa

The spatial and temporal urban land use and land cover change and its impact on climate for the city of Addis Ababa is investigated using land cover data from remote sensing satellite and spatial gridded climate data.

The result reveals that human activities have intensely changed land cover in urban area during the last decades. In the city the built-up areas have increased by121.88 km^2 within 25 years. The statistical result of the NDVI images over the subsequent periods show decreases in vegetation biomass.

In the year 2000 the population size was 2,112,737 and in the recent census of 2011 the population was 2,973,004, with an urban density of 5,608 persons per kilometer square. This is as compared to the year 2000 with a density of 1624 persons per kilometer square.
The result of historic daily nocturnal urban heat island (UHI) for the selected coldest year period of 1967-1968 shows that, the strongest warmest days in the city center in the month of November (about 6.0 ºC) and the month of April shows a reduction by about 5.8 ºC.

The population density influences the minimum temperature change as reflected by strong correlation (R^2=0.93). The minimum temperature increases from 1.02 to 1.99 ºC in most parts of the city. Under the A2 scenario, the highest urban warming will be occurring in October to December (2.5 ºC and 3.2 ºC) during the 2050s and 2080s. Interestingly, a weakening of the mean UHI intensity is expected during summer or Kiremt (long rainy season). Also the mean annual future UHI under RCP 8.5 scenario will increase by about 0.5 to 1 °C. The RCP 4.5 scenario also will increase by about 0.2 to 0.5 °C. In all A2, B2, RCP 4.5 and RCP 8.5 prediction scenario suggests more intense UHI events, in the months of October to December. The mean nocturnal UHI change also shows increases of Addis Ababa's nocturnal UHI and a high occurrence of intense heat island incidences in winter. Despite higher warming rate under the latest RCP scenarios as compared to SRES emission scenarios, UHI is more intense under SRES A2 and B2 scenarios than under RCP4.5 and RCP8.5 scenarios. This notable difference emanates from the fact that weaker warming spatial gradient under RCPs.

The research findings indicate that the urbanization influence on the climatological conditions is much higher during the dry season and have implications for thermal comfort planning and decision-making in the city. Hence measures that are capable of mitigating impacts of the increasing temperatures associated with the UHI are required in order to improve the city climate. One possible intervention could be to increase in urban green infrastructure including parks and other open spaces.

7.4 Recommendations for adaptation strategies

Ethiopia is a signatory to UNFCCC and ratified the Kyoto Protocol on climate change. This obligation resulted in strategy named “Climate-Resilient and Green Economy” (2011). Urban areas are the largest contributors to climate change through conversion of green cover like forest and grassland to other land use. From one of the result of this study the city of Addis Ababa will face climate change-related disputes on water supply. In chapter five, it was indicated that a rapid growth of the city projected to reach about 7 million people by 2039, most of the newly constructed mixed use buildings (commercial and residential) and new condominium housing in all sub-cities demands high water supply. From the WEAP water management results, this current study presents new methods for Addis Ababa on how water usage can be reduced to attain safe yields when planning for the projected population growth and change in climate. The future city water demand could be reduced through increased seasonal water prices, leakage reduction and technological water conservation measures. The results show that strict demand and supply policies can prevent even in the worst or dry climate and high population growth conditions including the unmet water demand which is about 449 and 516 million m^3 under both RCP 8.5 and RCP 4.5 scenarios.

From the result of water management options, Addis Ababa Water and Sewerage Authority (AAWSA) need to formulate a variety of adaptation plans, together with encouraging a culture of reducing water losses and rationing water use. However, community participation and awareness creation in planning and implementation need to be considered. Participatory water planning should be prioritized and recognized adaptations methods such as rainwater saving technologies (Pauw, *et al.*, 2011; Faramarzi, *et al.*, 2013). For example in New-South Wales, Australia, new houses in urban area required to use 40 % less potable water, through measures of water saving such as alternative shower heads, dual flush water-efficient toilets, grey water treatment systems and rainwater tanks (Werner and Collins, 2012).

Storm and waste water management adaptation strategies require increased focus on the impacts of heavy rainfall events. In the city of Addis Ababa the seasonal water supplies shortage occurred frequently. Reservoir expansions and new reservoir construction were proposed in the 20 years business plan of AAWSA.

Addis Ababa Water and Sewerage Authority Business Plan was developed in 2011 and identifies the most pressing water management issues and challenges facing the city and also present available opportunities and assets to achieve reliable water supplies through 2020. The AAWSA mission statement state that the agency will provide sufficient and reliable potable water supply and modern sewerage service to the City of Addis Ababa by exploiting available water sources and by developing sewer infrastructure in collaboration and with an integrated approach with stakeholders to satisfy the fast growing demand of the City for improved infrastructure. But with this AAWSA business plan did not consider climate change as part of the plan. It is recommended that the planning goals of AAWSA need to incorporate climate change impacts and leverage resources opportunities. It is recommended that Addis Ababa city government authorities act to improve drought or shortage of rain contingency planning to adapt to the climate change. Based on research finding of this current study it is strongly recommended that the future AAWSA Business plan incorporate water management framework and linkages to climate impact reduction.

7.4.1 Climate Change Management Plan for Adaptation for Water Sector

From the resent AAWSA Business Plan and from the results of this study (chapter 4-6) it is concluded that a new approach necessary for improved water resource and land use change management. The upcoming strategic water business plan for the city should incorporate as part of its Vision and Mission, the following four major points;

- Climate consideration: Shortage of precipitation and increased frequency of droughts are expected to create a shortage in water supply for some years. However, for other years rainfall expected to increase leading to higher volumes of water that resulted in increased price of water treatment due to an increase of sludge treatment. The short and long-range forecasts and information from national meteorological agency (NMA) could be used by AAWSA to optimally manage these aspects.

- Harvesting water treats rainwater as a resource rather than as a waste stream. The two main rainwater harvesting practices are disconnection downspout and the use of rain barrels. Disconnection of downspout is the process of directing roof runoff for irrigation purposes. Using rain barrels collects rainwater, diverting it from roof runoff directly into the storage containers. The collected water can be used for multiple purposes such as irrigation and flushing toilets. It is important to creating awareness among different stakeholders on vulnerabilities, impacts and adaptation options.
- Information exchange: Improved information exchange and data integration between development and investment stakeholders of the city (including AAWSA) and all sub-cities, notifying communities and stakeholders of all water plan actions and decisions through different media on the status of water supplies in the city.

The immediate, ongoing and changing conditions outlined above require that Addis Ababa fundamentally change how water use is managed as well as to account for future uncertainty. Efficiency of water use and conservation should become a priority at household level, as well as to other sectors of society, communities, industries and business. Action is required to deliver integrated, sustainable, reliable and secure water management systems for the current and growing economy as well as next generations. To accomplish this, a new business plan in AAWSA is required which includes climate change as integrated within its vision and goals, implementation plan with objectives and near-term and long-term actions removing water shortage obstacles.

7.4.2 Green Infrastructure as UHI adaptation intervention.

Several studies have anticipated that trees and other vegetation within building areas will reduce temperatures by about 2.7 °C when compared to non-green space areas (Akbari, *et al*., 2001; Kleerekoper *et al*., 2012; Onishi, *et al.*, 2010; Pitman, *et al.*, 2015). At larger scales, differences between non-vegetated city centers and vegetated areas have been shown to be as high as 5°C (Rosenzweig, *et al*., 2006; Wilby and Perry, 2006; Gerstenberg and Hofmann, 2016; Shishegar, 2014). Similarly, recent studies permeable (water) pavement have found that it reduces the negative impacts of UHI through its porosity that serves to protect the ground water better and allow more evaporative cooling (Oke, 2004; Chan, *et al*., 2008; Bowler, *et al*., 2010; Johns, *et al.*, 2011; Garrison and Horowitz, 2012; Nuruzzaman, 2015). Both of these effects help in cooling temperatures and mitigating the effect of UHI (Technology, 2010; Carmin, *et al*., 2012; Pitman *et al*., 2015). Climate change will alter ecosystem functions through changes in temperature of Urban Heat Islands (UHIs), precipitation regimes, evapo-transpiration, evaporation, humidity, soil moisture levels, vegetation growth rates (and allergen levels), water tables and aquifer levels, and air quality (IPCC,2013). These negative impacts accentuate the value of ecosystems services and green infrastructure for adaptation of UHI for the city of Addis Ababa.

"Green infrastructure" refers to interventions to preserve the functionality of existing green landscapes in the city of Addis Ababa and peripheral areas (including parks, forests, river-corridors and green belts), and to transform the built environment through remediation of river corridors and water-management techniques and by introducing productive landscapes including parks and vegetated open space. For UHI management, ecosystem based adaptation has relevance in urban areas of increased temperature as part of the climate change adaptation strategy seeks to move beyond a focus on street trees and parks to a more detailed understanding of the ecology of indigenous ecosystems, and how biodiversity and ecosystem services can reduce the vulnerability of ecosystems and people.

REFERENCE

AABoFED (Addis Ababa Bureau of Finance and Economic Development). (2013): Population Projection. *AABoFED,* Addis Ababa, Ethiopia.

AABoFED (Addis Ababa Bureau of Finance and Economic Development). *(2016): Growth and Transformation Plan II (GTP-2) of Addis Ababa and Socio-Economic Profile city administrations of Addis Ababa Finance and Economic Development.* Addis Ababa Bureau of Finance and Economic Development *(AABoFED).*

AACAILIC (Addis Ababa City Administration Integrated Land Information Centre). 2015: Addis Ababa City Administration map. City government of Addis Ababa AACAILIC. http://www.ilic.gov.et/index.php/en/subcities

AACPPO (Addis Ababa City Planning Project Office). (2014): Addis Ababa Land use development plan. Unpublished Planning document. AACPPO, Addis Ababa, Ethiopia.

AAWSA (Addis Ababa Water and Sewerage Authority). (1999). Water Supply and Upgrading Project. City Government of Addis Ababa Addis Ababa Water and Sewerage Authority (AAWSA) Addis Ababa Ethiopia.

AAWSA (Addis Ababa Water and Sewerage Authority). (2011): Water and Sanitation Development & Rehabilitation Project Office Unpublished Business Plan Phase II; City Government of Addis Ababa Addis Ababa Water and Sewerage Authority (AAWSA) Addis Ababa Ethiopia.

AAWSA (Addis Ababa Water and Sewerage Authority). (2012): Water production and distribution in Addis Ababa: Addis Ababa Water Supply and Sewerage Authority.

Abbate, E., Bruni, P., & Sagri, M. (2015). Geology of Ethiopia: A Review and Geomorphological Perspectives. In *Landscapes and Landforms of Ethiopia* (pp. 33–64). http://doi.org/10.1007/978-3-319-11800-0

Abeje, W. (2012). Sustainable Urban Mobility Planning for Coping Challenges of Urban Transportation in the Fast Urbanizing Ethiopia. *CODATU XV: The Role of Urban Mobility in (Re) shaping citiesCODATU*, (October), 11.

ACMAD-MESA (African Centre of Meteorological Applications for Development and Monitoring for Environment and Security in Africa). 2015: State of African Climate for 2014. ACMAD-MESA Climate Change Assessment Service, Version 1.0. pp15.

Addis Ababa City Government. 2012: Transportation challenges in a booming city Coordination of the mass transit network and urban development in Addis Ababa. CODATU, AACPPO Addis Ababa City Planning Project Office and Lyon Town Planning Agency. Vol.15. http://www.amiando.com/eventResources/c/r/dtIWGX0g1V16hI/Transportation_challenges_in_addis.pdf

Aguilar-Manjarrez, J., McDaid Kapetsky, J., & Soto, D. (2010). The potential of spatial planning tools to support the ecosystem approach to aquaculture. FAO Fisheries and Aquaculture Proceedings (FAO). Retrieved from http://agris.fao.org/agris-search/search.do?recordID=XF2006443717

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, *70*(3), 295–310. http://doi.org/10.1016/S0038-092X (00)00089-X

Akinbode, O. M., Eludoyin, A. O., & Fashae, O. A. (2008). Temperature and relative humidity distributions in a medium-size administrative town in southwest Nigeria. *Journal of Environmental Management*, *87*(1), 95–105. http://doi.org/10.1016/j.jenvman.2007.01.018

Alemayehu, T. (2001). The impact of uncontrolled waste disposal on surface water quality in Addis Ababa, Ethiopia. *SINET: Ethiopian Journal of Science*, *24*(1), 93–104. http://doi.org/10.4314/sinet.v24i1.18177

Alexander, D., Eric, D. & Michael, J. 2010: Climate Change and Urban Water Utilities: Challenges & Opportunist. Water P-Notes, World Bank Report. No. 50; 55828(1), 1-4.

Anderson, J. R., Hardy, E. E., Roach, J. T., Witmer, R. E., & Peck, D. L. (1976). A Land Use and Land Cover Classification System For Use With Remote Sensor Data. *A Revision of the Land Use Classification System as Presented in U.S. Geological Survey Circular 671*, *964*, 41.

Arakawa, A. 2004: The cumulus parameterization problem: past, present, and future. Journal of *Clim*ate *American Meteorological Society*. 17(13), 2493–2525. http://doi.org/10.1175/1520-0442 (2004)017<2493: RATCPP>2.0.CO; 2.

Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, *23*(1), 1–26. http://doi.org/10.1002/joc.859

Arsano, Y., Mekonnen, E., Gudisa, D., Achiso, D., Meally, S. O., Calow, R., & Ludi, E. (2010). Governance and Drivers of Change in Ethiopia's Water Supply Sector. *Structure*, 1–71. Retrieved from http://www.odi.org.uk/resources/download/4995.pdf

Babazadeh, M. & Kumar, P. (2015): Estimation of the Urban Heat Island in Local Climate Change and Vulnerability Assessment for Air Quality in Delhi; European Scientific Journal. 1, 55-65. ISSN: 1857- 743.

Baek, H. J., Lee, J., Lee, H. S., Hyun, Y. K., Cho, C., Kwon, W. T., … Byun, Y. H. (2013). Climate change in the 21st century simulated by HadGEM2-AO under representative concentration pathways. *Asia-Pacific Journal of Atmospheric Sciences*, *49*(5), 603–618. http://doi.org/10.1007/s13143-013-0053-7

Bahri A. (2012). Integrated Urban Water Management; Global Water Partnership Technical Committee (TEC). Global Water Partnership (GWP) Drottninggatan33 SE-111 51 Stockholm, Sweden.

Baklanov, A., Grimmond, C. S. B., Carlson, D., Terblanche, D., Tang, X., Bouchet, V., … Hovsepyan, A. (2017). From urban meteorology, climate and environment research to integrated city services. *Urban Climate*. http://doi.org/10.1016/j.uclim.2017.05.004

Baklanov, A., Hänninen, O., Slørdal, L. H., Kukkonen, J., Bjergene, N., Fay, B., … Sørensen, J. H. (2006). Integrated systems for forecasting urban meteorology, air pollution and population exposure. *Atmospheric Chemistry and Physics Discussions*, *6*(2), 1867–1913. http://doi.org/10.5194/acpd-6-1867-2006

Bates, B. C., Kundzewicz, Z. W., Wu, S., & Palutikof, J. P. (2008). *Climate Change and Water*. *Climate change and water*. http://doi.org/10.1016/j.jmb.2010.08.039

Bell, S. (2015). Renegotiating urban water. *Progress in Planning*, *96*, 1–28. http://doi.org/10.1016/j.progress.2013.09.001

Berhanu, B., Seleshi, Y., Demisse, S. S., & Melesse, A. M. (2015). Flow regime classification and hydrological characterization: A case study of Ethiopian rivers. Water (Switzerland), 7(6), 3149–3165. https://doi.org/10.3390/w7063149

Birkneh, T. (2007): Assessment Of Land Degradation Using Gis Based Model and Remote Sensing in Bishan Guracha-Adilo Sub-catchments, Southern Ethiopia. Addis Ababa University Unpublished Msc Thesis.

Block, A. H., Livesley, S. J., & Williams, N. S. G. (2012). Responding to the Urban Heat Island : A Review of the Potential of Green Infrastructure. *Victorian Centre,* 1–62. Retrieved from http://staging.202020vision.com.au/media/1026/responding-to-the-urban-heat-island-a-review-of-the-potential-of-green-infrastructure.pdf

Bloom D. E. & Canning D. (2011): Demographics and Development Policy. PGDA Working Paper. No. 66. http://www.hsph.harvard.edu/pgda/working.htm.

Bottyán, Z., Kircsi, A., Szegedi, S., & Unger, J. (2005). The relationship between built-up areas and the spatial development of the mean maximum urban heat island in Debrecen, Hungary. *International Journal of Climatology*, *25*(3), 405–418. http://doi.org/10.1002/joc.1138

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*. http://doi.org/10.1016/j.landurbplan.2010.05.006

Brian, L. (2009): Climate Change in Park City. An Assessment of Climate, Snowpack, and Economic Impacts. Stratus Consulting Washington, DC. SC11855.

Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B., & Jones, P. D. (2006). Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research*, *111*(D12), D12106. http://doi.org/10.1029/2005jd006548

Brown, C., Hansen, J. W. (2008): Agricultural Water Management and Climate Risk. Report to the Bill and Melinda Gates Foundation. International Research Institute for Climate and Society, Palisades, New York, USA. 8 (1), 1-19.

Burstyn, H. L. (2008). : The Emergence of Numerical Weather Prediction: Richardson's Dream. Isis, 99(3), 636–637. https://doi.org/10.1086/593259

Buytaert, W., & Bievre, B. D. (2012). Water for cities: The impact of climate change and demographic growth in the tropical Andes. *Water Resources Research, 48*(8). http://doi.org/10.1029/2011WR011755

Camilloni, I., & Barrucand, M. (2012). Temporal variability of the Buenos Aires, Argentina, urban heat island. *Theoretical and Applied Climatology*, *107*(1–2), 47–58. http://doi.org/10.1007/s00704-011-0459-z

Carlson, T. N., & Traci Arthur, S. (2000). The impact of land use - Land cover changes due to urbanization on surface microclimate and hydrology: A satellite perspective. *Global and Planetary Change*, *25*(1–2), 49–65. http://doi.org/10.1016/S0921-8181 (00)00021-7

Carmin, J., Anguelovski, I., & Roberts, D. (2012). Urban Climate Adaptation in the Global South: Planning in an Emerging Policy Domain. Journal of Planning Education and Research, 32(1), 18–32. https://doi.org/10.1177/0739456X11430951

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J., & Kazmierczak, A. (2015). Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, *95*, 1–66. http://doi.org/10.1016/j.progress.2013.08.001

Casterline, J. (2011). The pace of fertility transition: national patterns in the second half of the twentieth century. *Population and Development Review*, *27* (Supplement), 17–52. http://doi.org/10.2307/3115248

Chan, C. F., Lebedeva, J., Otero, J., & Richardson, G. (2008). Urban heat islands: A climate change adaptation strategy for Montreal. *Plan Canada*. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-53349160734&partnerID=40&md5=9d72b6ef4bb0ed889ffc4dfb139661b3

Charabi, Y., & Bakhit, A. (2011). Assessment of the canopy urban heat island of a coastal arid tropical city: The case of Muscat, Oman. *Atmospheric Research*, *101*(1–2), 215–227. http://doi.org/10.1016/j.atmosres.2011.02.010

Chaturvedi, R. K., Joshi, J., Jayaraman, M., Bala, G., & Ravindranath, N. H. (2012). Multi-model climate change projections for India under representative concentration pathways. Current Science, 103(7), 791–802.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., … Whetton, P. (2007). Regional Climate Projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 848–940). http://doi.org/10.1080/07341510601092191

Cincotta, R., C. 2010: The Future of Sub-Saharan Africa's Fertility Decline. *New security Beat.* http://www.newsecuritybeat.org/2010/08/future-of-sub-sharan-africas-tentative_25.html

Cleugh, H., & Grimmond, S. (2012). Urban Climates and Global Climate Change. In The Future of the World's Climate (pp. 47–76). https://doi.org/10.1016/B978-0-12-386917-3.00003-8

CLUVA (Climate Change and Urban Vulnerability African Cities). (2010): Assessing Vulnerability of Urban Systems, Populations and Goods in Relation to Natural and Man-Made Disasters in Africa. Report on the Seventh Framework Programme on Hazard Scenario Impacts for the Six Climate Change Models.

Coquard, J., Duffy, P. B., Taylor, K. E., & Iorio, J. P. (2004). Present and future surface climate in the western USA as simulated by 15 global climate models. *Climate Dynamics*, *23*(5), 455–472. http://doi.org/10.1007/s00382-004-0437-6

Costa-Cabral, M., Coats, R., Reuter, J., Riverson, J., Sahoo, G., Schladow, G., … Chen, L. (2013). Climate variability and change in mountain environments: some implications for water resources and water quality in the Sierra Nevada (USA). *Climatic Change*, *116*(1), 15–16. http://doi.org/10.1007/s10584-012-0647-6

Cox, W., & Hugh, P. (2014). 11th Annual Demographia International Housing Affordability Survey: 2015. *Performance Urban Planning*, *11*(4), 59. Retrieved from http://www.demographia.com/dhi.pdf

CSA (Central Statistics Authority of Ethiopia). 2011: Demographic survey for the city of Addis Ababa. CSA, Ethiopia.

CSA (Central Statistics Authority of Ethiopia). (2007). Population and Housing Census 2007 Report. Central Statistical Agency, Addis Ababa. Retrieved from http://www.csa.gov.et/surveys/Population and Housing census/ETH-pop-2007/survey0/data/Doc/Reports/National_Statistical.pdf

CSA (Central Statistics Authority of Ethiopia). 2000: Demographic survey for the city of Addis Ababa. CSA, Ethiopia.

CSA (Central Statistics Authority of Ethiopia). 2008: Demographic survey for the city of Addis Ababa. CSA, Ethiopia.

CSA (Central Statistics Authority of Ethiopia). 2013: Population projection and National Demographic survey for the cities in Ethiopia. CSA, Ethiopia.

Dastagir, M. R. (2015). Modeling recent climate change induced extreme events in Bangladesh: A review. *Weather and Climate Extremes*, *7*, 49–60. http://doi.org/10.1016/j.wace.2014.10.003

Davis, M. (2004). Planet of slums: Urban involution and the informal proletariat. *New Left Review*. http://doi.org/10.1215/0961754X-2008-032

Degefu, W. (1987): Some aspects of meteorological drought in Ethiopia. In: Krenz, M. E. (1985) (ed.), Drought and hunger in Africa: Denying famine a future. *Cambridge University Press*, UK. 23-36.

Dinku, T., Asefa, K., Hilemariam, K., Grimes, D., & Connor, S. (2011). Improving availability, access and use of climate information. *WMO Bulletin*, *60*(2), 80–86. Retrieved from http://public.wmo.int/en/bulletin/improving-availability-access-and-use-climate-information

Droogers, P. 2009: Climate Change and Hydropower, Impact and Adaptation Costs: Case Study Kenya. Future Water-Costerweg, Wageningen, Netherlands.

Edwards, P. N. (2010). A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming. *Thinking*, 518. http://doi.org/10.1111/j.1541-1338.2011.00522_3.x

Edwards, P. N. (2011). History of climate modeling. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(1), 128–139. http://doi.org/10.1002/wcc.95

EEA (Ethiopian Economics Association). (2011): Research Report on Spatial Equity in the Provision of WaSH services: Evidence from Selected Area-Based Case Studies. Ethiopian Economics Association (EEA) and Water-Aid Ethiopia, Addis Ababa Ethiopia.

Elala, D. (2011). Vulnerability assessment of surface water supply systems due to climate change and other impacts in Addis Ababa, Ethiopia. Department of Earth Sciences, Aquatic Climatology, Uppsala University, Sweden. ISSN 1401-5765.

Eriyagama, N.; Smakhtin, V.; Chandrapala, L.; Fernando, K. (2010). *Impacts of Climate Change on Water Resources and Agriculture in Sri Lanka: A Review and Preliminary Vulnerability Mapping*. *International Water Management Institute*.

FAO. *(*2001). FAOCLIM 2.0 A World-Wide Agro-climatic Database. *Food and Agriculture Organization of the United Nations:* Rome, Italy.

Faramarzi, M., Abbaspour, K. C., Ashraf Vaghefi, S., Farzaneh, M. R., Zehnder, A. J. B., Srinivasan, R., & Yang, H. (2013). Modeling impacts of climate change on freshwater availability in Africa. *Journal of Hydrology*, 480, 85–101. https://doi.org/10.1016/j.jhydrol.2012.12.016

FDRE (Federal Democratic Republic of Ethiopia). (2011). Climate-Resilient and Green economy strategy. *Federal Democratic Republic of Ethiopia*.

Fekadu, K. (2015). Ethiopian Seasonal Rainfall Variability and Prediction Using Canonical Correlation Analysis (CCA). *Earth Sciences, 4*(3), 112. http://doi.org/10.11648/j.earth.20150403.14

Fernando, H.J.S. 2013: Hand book of Environmental Fluid Dynamics and Urban Heat Island. CRC Press Taylor & Francis Group. ISBN: 978-1-4665-5601-0.

Fisher, P., Kukkonen, J., Piringer, M., Rotach, M. W., & Schatzmann, M. (2005). Meteorology applied to urban air pollution problems: concepts from COST 715. *Atmospheric Chemistry and Physics Discussions, 5*(4), 7903–7927. http://doi.org/10.5194/acpd-5-7903-2005

Foster, V., & Morella, E. (2011). Ethiopia's Infrastructure: a Continental Perspective. *World Bank Policy Research Working Paper No. 5595*. http://doi.org/http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2011/03/17/000158349_20110317145909/Rendered/PDF/WPS5600.pdf

García-Cueto, O. R., Jáuregui-Ostos, E., Toudert, D., & Tejeda-Martinez, A. (2007). Detection of the urban heat island in Mexicali, B. C., México and its relationship with land use. *Atmosfera*, *20*(2), 111–131.

Garrison, Noah; Horowitz, Cara; Lunghino, Chris Ann; Devine, Jon; and Beckman, D. S. (2012). *Looking Up: how Green Roofs and Cool Roofs Can Reduce Energy Use, Address Climate Change, and Protect Water Resources in Southern California*. *Nrdc Report* (Vol. R: 12-06-B). Retrieved from http://www.nrdc.org/water/pollution/files/greenroofsreport.pdf

Gebre, G., & Rooijen, D. (2009). Urban water pollution and irrigated vegetable farming in Addis Ababa. In *Water, sanitation and hygiene: sustainable development and multisectoral approaches* (p. 6).

Gerstenberg, T., & Hofmann, M. (2016). Perception and preference of trees: A psychological contribution to tree species selection in urban areas. *Urban Forestry and Urban Greening*, *15*, 103–111. http://doi.org/10.1016/j.ufug.2015.12.004

Giorgi, F., & Mearns, L. O. (2002). Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the "Reliability Ensemble Averaging" (REA) method. *Journal of Climate*, *15*(10), 1141–1158. http://doi.org/10.1175/1520-0442 (2002)015<1141:COAURA >2.0.CO;2

Gissila, T., Black, E., Grimes, D. I. F., & Slingo, J. M. (2004). Seasonal forecasting of the Ethiopian summer rains. *International Journal of Climatology*, *24*(11), 1345–1358. http://doi.org/10.1002/joc.1078

Golden, J. S., Carlson, J., Kaloush, K. E., & Phelan, P. (2007). A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures. *Solar Energy*, *81*(7), 872–883. http://doi.org/10.1016/j.solener.2006.11.007

Golini, A., Said, M., Casacchia, O., Reynaud, C., Basso, S., Cassata, L. & Crisci, M. 2001: In depth report on Migration and Urbanization in Ethiopia with a Special Reference to Addis Ababa. DSD (Department of Demographic) Science, University of Roma and CSA (Central Statistical Authority, Addis Ababa) Ethiopia.

Gonfa, L. 1996: Climate Classification of Ethiopia. National Meteorological Services of Ethiopia Bulletin, Addis Ababa, Ethiopia.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., … Wood, R. A. (2000). The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*, *16*(2–3), 147–168. http://doi.org/10.1007/s003820050010

Gregory, J. M., & Forster, P. M. (2008). Transient climate response estimated from radiative forcing and observed temperature change. *Journal of Geophysical Research Atmospheres*, *113*(23). http://doi.org/10.1029/2008JD010405

Grimmond, C. S. B. (2006). Progress in measuring and observing the urban atmosphere. *Theoretical and Applied Climatology*. http://doi.org/10.1007/s00704-005-0140-5

Grimmond, C. S. B., Carmichael, G., Lean, H., Baklanov, A., Leroyer, S., Masson, V., Schluenzen, H., & Golding, B. 2015:Urban-Scale Environmental Prediction Systems, Chapter 18. WMO Bulletin, 1156.

Grimmond, S., Beig, G., Brown, B., Carmichael, G., Chen, B., Fang, Z., Fleming, G., Garcia, A., Jalkanen, L., Kootval, H., L. I. H., Longo, K., Haizen, M. U., Peng, L., Jianping, S. H. I., Tan, J., Tang, X., Terblanche, D., Woo, W. C.& Zhang, J. 2014: Towards integrated urban weather, environment and climate services. WMO Bulletin. 63 (1), 10-14.

Grimmond, S., Roth, M., Oke, T., Au, Y.C., Best, M., Betts, R., Carmichael, G., Cleugh, H., Dabberdt, W., Emmanuel, R., Freitas, E., Fortuniak, K., Hanna, S., Klein, O., Kalkstein, L.S., Liu, C.H., Nickson, A., Pearlmutter, D., Sailor, D., & Voogt, J. (2010). Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities. Journal of Procedia Environmental Sciences, 1,247-274.

Hanak, E., & Lund, J. R. (2011). Adapting California's water management to climate change. *Climatic Change*, 28. http://doi.org/10.1007/s10584-011-0241-3

Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. *Rev. Geophys.*, *48*(4), RG4004. http://doi.org/10.1029/2010RG000345.1.INTRODUCTION

Harma, K. J., Johnson, M. S., & Cohen, S. J. (2012). Future Water Supply and Demand in the Okanagan Basin, British Columbia: A Scenario-Based Analysis of Multiple, Interacting Stressors. Water Resources Management, 26(3), 667–689. https://doi.org/10.1007/s11269-011-9938-3

Hashmi, M. Z., Shamseldin, a. Y., & Melville, B. W. (2009). Statistical downscaling of precipitation: state-of-the-art and application of bayesian multi-model approach for uncertainty assessment. *Hydrology and Earth System Sciences Discussions*, *6*, 6535–6579. http://doi.org/10.5194/hessd-6-6535-2009

Hayhoe, K., Stoner, A. & Gelca, R. (2013): Climate Change Projections and Indicators for Delaware. Journal of ATMOS Research & Consulting, 1, 1-56.

Henriques, C. (2007). Hydrology and water resources management in East Anglia and North West England in the context of climate and socio-economic change. *Applied Sciences*, 213.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). WORLDCLIM - a set of global climate layers (climate grids). *International Journal of Climatology*, *25*, 1965–1978. Retrieved from http://www.worldclim.org/

Hill, C., DeLuca, C., Balaji, Suarez, M., & Da Silva, A. (2004). The architecture of the Earth system modeling framework. *Computing in Science and Engineering*, *6*(1), 18–28. http://doi.org/10.1109/MCISE.2004.1255817

Hoff, H., Nole, S. & Droogers, P. 2007: Water Use and Demand in the Tana Basin; Analisis using the Water Evaluation and Planning tool (WEAP).Green Water Credits. http://www.weap21.org/downloads/GWC_Report_4.pdf

Hoffmann, P., Krueger, O., & Schlünzen, K. H. (2011). A statistical model for the urban heat island and its application to a climate change scenario. *International Journal of Climatology*, *32*(May 2011), n/a-n/a. http://doi.org/10.1002/joc.2348

Howard, G., Katrina, C., Pond, K., Brookshaw, A., Hossain, R., & Bartram, J. (2010). Securing 2020 vision for 2030: Climate change and ensuring resilience in water and sanitation services. *Journal of Water and Climate Change*, *1*(1), 2–16. http://doi.org/10.2166/wcc.2010.205

Htut, A. Y., Shrestha, S., Nitivattananon, V. & Kawasaki, A. 2014: Forecasting Climate Change Scenarios in the Bago River Basin, Myanmar. Journal of Earth Science and climate change, 5(9), 1-11. http://dx.doi.org/10.4172/2157-7617.1000228

Hunt, A., & Watkiss, P. (2010). Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, *104*(1), 13–49. https://doi.org/10.1007/s10584-010-9975-6

Hurd, B. H., Leary, N., Jones, R., Smith, J., Leary, N., Jones, R., … Smith, J. (1999). Relative Regional Vulnerability of Water Resources to Climate Change. *Journal of The American Water Resources Association*, *35*(6), 1399–1409. https://doi.org/10.1111/j.1752-1688.1999.tb04224.x

Im, E. S., Ahn, J. B., & Jo, S. R. (2015). Regional climate projection over South Korea simulated by the HadGEM2-AO and WRF model chain under RCP emission scenarios. *Climate Research*, *63*(3), 249–266. https://doi.org/10.3354/cr01292

IPCC. (2001). Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. *Climate Change 2001: The Scientific Basis.*, *446*(November), 881. https://doi.org/10.1256/004316502320517344

IPCC. (2007). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press, Cambridge, United Kingdom and New York, {NY}, {USA}*: 996 pp.

IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change*. *Ipcc*. http://doi.org/10.1596/978-0-8213-8845-7

IPCC. (2013). Working Group 1, I., Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., … Midgley, P. M. (2013). IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, AR5, 1535.

IPCC. (2014a). Summary for Policymakers. *Climate Change 2014: Impacts, Adaptation and Vulnerability - Contributions of the Working Group II to the Fifth Assessment Report*, 1–32. https://doi.org/10.1016/j.renene.2009.11.012

IPCC. (2014b). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*, 688. https://doi.org/10.1017/CBO9781107415324.004

Jensen, J. R., & Lulla, K. (1987). Introductory digital image processing: A remote sensing perspective. *Geocarto International*, *2*(1), 65. http://doi.org/10.1080/10106048709354084

Jensen, R. (2004): *Introductory Digital Image Processing*; Remote SensingPerspective. Third Edition. Book ofPrentice Hall, Publisher. ISBN-13:978-0131453616.

Johns, T. C., Royer, J. F., Höschel, I., Huebener, H., Roeckner, E., Manzini, E., … Hewitt, C. D. (2011). Climate change under aggressive mitigation: The ENSEMBLES multi-model experiment. *Climate Dynamics*, *37*(9–10), 1975–2003. https://doi.org/10.1007/s00382-011-1005-5

Jones, P. D., & Hulme, M. (1996). Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. *International Journal of Climatology*, *16*, 361–377. https://doi.org/10.1002/ (SICI) 1097-0088(199604)16:4<361: AID-JOC53>3.0.CO; 2-F

Keller, M. (2009). Climate Risks and Development Projects. *Assessment Report for a Community-Level Project in Guduru, Oromia, Ethiopia*, (November), 1–35.

Keyantash, J., & Dracup, J. A. (2002). The quantification of drought: An evaluation of drought indices. *Bulletin of the American Meteorological Society*. http://doi.org/10.1175/1520-0477 (2002)083<1191: TQODAE>2.3.CO; 2

Khan, M. S., Coulibaly, P., & Dibike, Y. (2006). Uncertainty analysis of statistical downscaling methods. *Journal of Hydrology*, *319*(1–4), 357–382. https://doi.org/10.1016/j.jhydrol.2005.06.035

Kifle, A. B. (2003). Urban Heat Island and Its Feature in Addis Ababa (a Case Study). Fifth International Conference on Urban Climate, Lodz, Poland. http://nargeo.geo.uni.lodz.pl/~icuc5/text/P_6_11.pdf

Kifle, A. B. (2006): Urban Climate News; City Report Addis Ababa. International Association for Urban Climate (IAUC). Issue No.17.

Kleerekoper, L., Van Esch, M., & Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2011.06.004

Knutti, R., & Sedláček, J. (2012). Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, *3*(4), 369–373. https://doi.org/10.1038/nclimate1716

Knutti, R., & Tomassini, L. (2008). Constraints on the transient climate response from observed global temperature and ocean heat uptake. *Geophysical Research Letters*, *35*(9). https://doi.org/10.1029/2007GL032904

Korecha, D., & Barnston, A. G. (2007). Predictability of June–September Rainfall in Ethiopia. *Monthly Weather Review*, *135*(2), 628–650. https://doi.org/10.1175/MWR3304.1

Kotharkar, R., & Surawar, M. (2016). Land Use, Land Cover, and Population Density Impact on the Formation of Canopy Urban Heat Islands through Traverse Survey in the Nagpur Urban Area, India. *Journal of Urban Planning and Development*, *142*(1), 4015003. https://doi.org/10.1061/ (ASCE) UP.1943-5444.0000277

Kreft, S., Harmeling, S., Bals, C., Zacher, W. & Van, de Sand, K. 2010. The millennium development goals (MDG) and climate change: taking stock andlooking ahead. German watch.www.germanwatch.org/klima/klimdg10e.htm

Kuttler, W., Weber, S., Schonnefeld, J., & Hesselschwerdt, A. (2007). Urban/rural atmospheric water vapour pressure differences and urban moisture excess in Krefeld, Germany. In *International Journal of Climatology* (Vol. 27, pp. 2005–2015). https://doi.org/10.1002/joc.1558

Lansigan, F. P., & Salvacion, A. R. (2007). Assessing The Effect Of Climate Change On Rice And Corn Yields In Selected Provinces In The Philippines by. In *10th National Convention on Statistics (NCS)* (pp. 1–12).

Larson, K. L., Polsky, C., Gober, P., Chang, H., & Shandas, V. (2013). Vulnerability of water systems to the effects of climate change and urbanization: A comparison of phoenix, Arizona and Portland, Oregon (USA). *Environmental Management*, *52*(1), 179–195. https://doi.org/10.1007/s00267-013-0072-2

LCCP. 2006: Adapting to Climate Change: Lessons for London. London Climate Change Partnership. Greater London Authority, London.

Leulsegged, K., Gete, Z., Dawit, A., Fitsum, H., & Andreas, H. (2012). Impact of urbanization of addis abeba city on peri-urban environment and livelihoods. *The Tenth Conference on Ethiopian Economy*, 1–30.

Lévite, H., Sally, H., & Cour, J. (2003). Testing water demand management scenarios in a water-stressed basin in South Africa: Application of the WEAP model. *Physics and Chemistry of the Earth*, *28*(20–27), 779–786. https://doi.org/10.1016/j.pce.2003.08.025

Lobell, D. B., Bonfils, C., & Duffy, P. B. (2007). Climate change uncertainty for daily minimum and maximum temperatures: A model inter-comparison. *Geophysical Research Letters*, *34*(5). https://doi.org/10.1029/2006GL028726

London Climate Change Partnership (LCCP). 2002: A Climate Change Impacts in London Evaluation Study final technical report. London Climate Change Partnership, Greater London Authority, London.UK

Mahmood, R. & Babel, S. M. (2014): Future changes in extreme temperature events using the statistical downscaling model (SDSM) in the trans-boundary region of the Jhelum river basin. Weather and Climate Extremes journal. 5(6), 56–66.

Makhelouf, A. (2009). The effect of green spaces on urban climate and pollution. *Journal of Environmental Health Science & Engineering*, *6*(1), 35–40.

Manabe, S., & Wetherald, R. T. (1975). The Effects of Doubling the CO2 Concentration on the climate of a General Circulation Model. *Journal of the Atmospheric Sciences*, *32*(1), 3–15. https://doi.org/10.1175/1520-0469 (1975)032<0003: TEODTC>2.0.CO; 2

Manawadu, L. & Nirosha, L. 2008: Identifying Surface Temperature Pattern of the City of Colombo, Jornal of Engineering. 41(5), 133-140.

Mantyka-Pringle, C. S., Martin, T. G., & Rhodes, J. R. (2013). Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. *Global Change Biology*, *19*(5), 1642–1644. https://doi.org/10.1111/gcb.12148

Manzungu, E., & Machiridza, R. (2005). An analysis of water consumption and prospects for implementing water demand management at household level in the City of Harare, Zimbabwe. *Physics and Chemistry of the Earth*, *30*(11–16 SPEC. ISS.), 925–934. https://doi.org/10.1016/j.pce.2005.08.039

Martilli, A. (2007). Current research and future challenges in urban mesoscale modelling. In *International Journal of Climatology* (Vol. 27, pp. 1909–1918). https://doi.org/10.1002/joc.1620

Martin, G. M., Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R., Hardiman, S. C., … Wiltshire, A. (2011). The HadGEM2 family of Met Office Unified Model climate configurations. *Geoscientific Model Development*, *4*(3), 723–757. https://doi.org/10.5194/gmd-4-723-2011

Mccartney, M. P., & Arranz, R. (2007). Evaluation of Historic, Current and Future Water Demand in the Olifants River Catchment, South Africa. International Water Management Institute. https://doi.org/http://dx.doi.org/10.3910/2009.118

McGuffie, K., & Henderson-Sellers, A. (2005). *A Climate Modelling Primer*. *A Climate Modelling Primer*. https://doi.org/10.1002/0470857617

Meehl, G. A., Covey, C., McAvaney, B., Latif, M., & Stouffer, R. J. (2005). Overview of the coupled model intercomparison project. *Bulletin of the American Meteorological Society*, *86*(1), 89–93. https://doi.org/10.1175/BAMS-86-1-89

Melese, M. (2005). City Expansion, Squatter Settlements and Policy Implications in Addis Ababa: The Case of Kolfe Keranio Sub-City. *Acta Geographica-Trondheim*, *Serie A* (Nr. 9), 2–28. https://doi.org/10.4314/ejossah.v2i2.29866

MESP (Ministry of Environment and Spatial Planning). 2009: Institutional Support to Ministry of Environment and Spatial Planning and River Basin Authorities. WEAP: a tool for Drini River Basin Planning WEAP Modelling Manual. Violeta Hoxha, Ministry of Environment and Spatial Planning, Republic of Kosovo.

MESP (Ministry of Environment and Spatial Planning). 2011: Water Security for Central Kosovo Model for Water Resource Planning. World Bank. Kosovo.

MoFED (Ministry of Finance and Economic Development). 2005: Plan for Accelerated and Sustained Development to End Poverty (PASDEP). MoFED Addis Ababa, Ethiopia.

MoFED (Ministry of Finance and Economic Development). 2012: Growth and Transformation Plan (GTP) and Ethiopian Millennium Development Goals Report. MoFED Addis Ababa, Ethiopia.

MoH & MoWE. 2011: Ministry of Health and Ministry of Water and Energy Summary of Universal Access Plan and implementation of water supply and hygiene program (WaSH); Ministry of Water and Energy (MoWE).

Mohan, M. (2011). Urban Heat Island Effect over National Capital Region of India: A Study using the Temperature Trends. *Journal of Environmental Protection*, *2*(June), 465–472. https://doi.org/10.4236/jep.2011.24054

Mohan, M., Kikegawa, Y., Gurjar, B. R., Bhati, S., & Kolli, N. R. (2013). Assessment of urban heat island effect for different land use-land cover from micrometeorological measurements and remote sensing data for megacity Delhi. *Theoretical and Applied Climatology*, *112*(3–4), 647–658. https://doi.org/10.1007/s00704-012-0758-z

Morita, T., Nakićenović, N., & Robinson, J. (2000). Overview of mitigation scenarios for global climate stabilization based on new IPCC emission scenarios (SRES). *Environmental Economics and Policy Studies*, *3*(2), 65–88. https://doi.org/10.1007/BF03354031

Morris, C. J. G., Simmonds, I., & Plummer, N. (2001). Quantification of the Influences of Wind and Cloud on the Nocturnal Urban Heat Island of a Large City. *Journal of Applied Meteorology*, *40*(2), 169–182. https://doi.org/10.1175/1520-0450(2001)040<0169:QOTIOW>2.0.CO;2

Morrison, H., McCoy, R. B., Klein, S. A., Xie, S., Luo, Y., Avramov, A., … Zhang, G. (2009). Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. II: Multilayer cloud. *Quarterly Journal of the Royal Meteorological Society*, *135*(641), 1003–1019. https://doi.org/10.1002/qj.415

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., … Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747–756. https://doi.org/10.1038/nature08823

MoUDHC (Ministry of Urban Development, Housing and Construction). 2014: National Report on Housing & Sustainable Urban Development. Ministry of Urban Development, Housing and Construction (MUDHC), Addis Ababa Ethiopia.

Mounir, Z. M., Ma, C. M., & Amadou, I. (2011). Application of water evaluation and planning (WEAP): A model to assess future water demands in the Niger River (in Niger Republic). *Modern Applied Science*, *5*(1), 38–49.

MoWR (Ministry of Water Resource). 2008: Reformulation of plans and strategies of rural water supply of Universal Access Program (UAP) for accelerated implementation. A presentation prepared for UAP performance evaluation conference, Addis Ababa, Ethiopia.

Mulwafu, W., Chipeta, C., Chavula, G., Ferguson, A., Nkhoma, B. G., & Chilima, G. (2003). Water demand management in Malawi: Problems and prospects for its promotion. *Physics and Chemistry of the Earth*, *28*(20–27), 787–796. https://doi.org/10.1016/j.pce.2003.08.003

Nakicenovic, N., & Swart, R. (2000). IPCC Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change. *Emissions Scenarios*, 608.

Nebeker, F. (1999). Calculating the Weather Meteorology in the 20th Century. In *Knowledge Creation Diffusion Utilization* (pp. 27–35).

Nemry, F., & Demirel, H. (2012). *Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures. JRC72217. European Commission, Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS)*. https://doi.org/10.2791/15504

Nimusiima, A., Basalirwa, C., Majaliwa, J., Mbogga, S., Mwavu, E., Namaalwa, J., & Okello-Onen, J. (2014). Analysis of Future Climate Scenarios over Central Uganda Cattle Corridor. *Journal of Earth Science & Climatic Change*, *5*(10). https://doi.org/10.4172/2157-7617.1000237

NMA (National Meteorological Agency of Ethiopia). 2007: Climate Change National Adaptation Programme of Action (NAPA) of Ethiopia. The World Bank. http://unfccc.int/resource/docs/napa/eth01.pdf

NOAA. (2015). What is the difference between land cover and land use? Retrieved from http://oceanservice.noaa.gov/facts/lclu.html

NOAA/NCEP/CPC/CAMS. 2015. Anomaly temperature / root mean and anomalies: temperature anomaly data. NOAA. http://oceanservice.noaa.gov/facts/lclu.htm

NRC (National Research Council). 2010: When Weather Matters: Science and Service to Meet Critical Societal Needs. The National Academies Press. Washington, DC. ISBN: 978-0-309-15249-5 http://www.nap.edu/openbook.php?record_id=12888.

NRC (National Research Council). 2012: Urban Meteorology: Forecasting, Monitoring, and Meeting Users' Needs. Washington, DC: The National Academies Press.Washington, DC. ISBN: 978-0-309-25217-1http://www.nap.edu/openbook.php?record_id=13328.

Nugent, R. and Seligman, B. (2008): Demographics and Development in the 21st Century Initiative Technical Background Paper, How Demographic Change Affects Development, Center for Global Development, Washington DC.

Nuruzzaman, M. (2015). Urban Heat Island: Causes, Effects and Mitigation Measures - A Review. *International Journal of Environmental Monitoring and Analysis*, *3*(2), 67. https://doi.org/10.11648/j.ijema.20150302.15

OECD. (2016). African Economic Outlook 2016. *Sustainable Cities and Structural Transformation*, 397. http://doi.org/http://dx.doi.org/10.1787/aeo-2016-en

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, *108*(455), 1–24. https://doi.org/10.1002/qj.49710845502

Oke, T. R. (1987). *Boundary Layer Climates*. *Earth-Science Reviews* (Vol. 27). https://doi.org/10.1016/0012-8252 (90)90005-G

Oke, T. R. (2004). Initial guidance to obtain representative meteorological observations at urban sites. *World Meteorological Organization*, (81), 51. https://doi.org/Reporte

Olaide, A.M., Kayod,e S.E., E dris, I. 2013: An Assessment of Urban Heat Island in Akure Using Geospatial Techniques. IOSR Journal of Environmental Science, Toxicology And Food Technology. 6, 24-34.

Onishi, A., Cao, X., Ito, T., Shi, F., & Imura, H. (2010). Evaluating the potential for urban heat-island mitigation by greening parking lots. *Urban Forestry and Urban Greening*, *9*(4), 323–332. https://doi.org/10.1016/j.ufug.2010.06.002

ORAAMP (Office of the Revision Addis Ababa Master Plan). 2002: Addis Ababa Master Plan 2001 - 2010, Executive Summery. Addis Ababa City Administration, Addis Ababa, Ethiopia.

Pacific Institute (PACINST). 2006: Remaining drops: Freshwater resources. A global issue. Pacific Institute and Bio Economic Research Associates. http://www.pacinst.org/reports/remaining_drops/CLSA_U_remaining_drops.pdf

Parry, M.; Canziani, O.; Palutikof, J.; van der Linden, P.; Hanson, C. (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. *IPPC: Climate Change 2007: Impacts, Adaptation and Vulnerability*, 976. https://doi.org/10.2134/jeq2008.0015br

Pauw, P. & Boateng-Gyimah, M. 2011: Water resource planning in times of climate change A WEAP exercise in the Dayi River basin in Ghana. Institute voor Milieuvraagstukken. Ghana.

Peña, M. A. (2008). Relationships between remotely sensed surface parameters associated with the urban heat sink formation in Santiago, Chile. *International Journal of Remote Sensing*, *29*(15), 4385–4404. https://doi.org/10.1080/01431160801908137

Petersen, A. C. (2006). *Simulating nature: a philosophical study of computer-simulation uncertainties and their role in climate science and policy advice*. *Distribution*. https://doi.org/10.1080/02664763.2012.749047

Pinet, P. R. (2014). *Megacities and the coast: risk, resilience and transformation*. *CHOICE: Current Reviews for Academic Libraries VO - 52*. https://doi.org/10.4324/9780203066423

Pitman, S. D., Daniels, C. B., & Ely, M. E. (2015). Green infrastructure as life support: Urban nature and climate change. Transactions of the Royal Society of South Australia, 139(1), 97–112. https://doi.org/10.1080/03721426.2015.1035219

Potter, S. (2009). Weather by the Numbers: The Genesis of Modern Meteorology. Weatherwise, 62(3), 49. http://doi.org/10.1093/envhis/emq010

Praskievicz, S., & Chang, H. (2009). A review of hydrological modelling of basin-scale climate change and urban development impacts. Progress in Physical Geography, 33(5), 650–671. https://doi.org/10.1177/0309133309348098

Rai P. V. S., Mishra, A., and Onagh, M. (2011). Multi-Seasonal Irs-1c Liss Iii Satellite Data for Change Detection Analysis. Acadamy Scicnce Jornal; GIS Trends. 2(1), 13-19.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., … Taylor, K. E. (2007). Climate Models and Their Evaluation. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 589–662). https://doi.org/10.1016/j.cub.2007.06.045

Raskin, P., Hansen, E., Zhu, Z., IWRA, M., & Stavisky, D. (1992). Simulation of Water Supply and Demand in the Aral Sea Region. *Water International*, *17*(2), 55–67. https://doi.org/10.1080/02508069208686127

Riahi, K., Grübler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, *74*(7), 887–935. https://doi.org/10.1016/j.techfore.2006.05.026

Rizwan, A. M., Dennis, L. Y. C., & Liu, C. (2008). A Review on the Generation, Determination And Mitigation of Urban Heat Island. *Journal of Environmental Sciences*, *20*(1), 120–128. Https://Doi.Org/10.1016/S1001-0742 (08)60019-4

Rochdane, S., Reichert, B., Messouli, M., Babqiqi, A., & Khebiza, M. Y. (2012). Climate Change Impacts on Water Supply and Demand in Rheraya Watershed (Morocco), with Potential Adaptation Strategies. *Water*, *4*(4), 28–44. https://doi.org/10.3390/w4010028

Roe, G. H., & Baker, M. B. (2007). Why Is Climate Sensitivity So Unpredictable? *Science*, *318*(5850), 629–632. https://doi.org/10.1126/science.1144735

Rosa, G., & Clasen, T. (2010). Estimating the scope of household water treatment in low- and medium-income countries. *American Journal of Tropical Medicine and Hygiene*, *82*(2), 289–300. https://doi.org/10.4269/ajtmh.2010.09-0382

Rosenzweig, C., Solecki, W., & Slosberg, R. (2006). Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. *86th AMS Annual Meeting*, 5. Retrieved from http://www.giss.nasa.gov/research/news/20060130/103341.pdf

Roy, S. B., Chen, L., Girvetz, E., P, E., Mills, W. B., & Grieb, T. M. (2010). Evaluating Sustainability of Projected Water Demands under Future Climate Change Scenarios. Tetra Tech, 40.

Salzmann, N., Frei, C., Vidale, P. L., & Hoelzle, M. (2007). The application of Regional Climate Model output for the simulation of high-mountain permafrost scenarios. *Global and Planetary Change*, *56*(1–2), 188–202. https://doi.org/10.1016/j.gloplacha.2006.07.006

Samadi, S., Carbone, G. J., Mahdavi, M., Sharifi, F., & Bihamta, M. R. (2013). Statistical Downscaling of River Runoff in a Semi Arid Catchment. *Water Resources Management*, *27*(1), 117–136. https://doi.org/10.1007/s11269-012-0170-6

Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2013.05.047

Sarkar, H. 2004: Study of Land cover and Population Density Influences on Urban Heat Island in Tropical Cities by Using Remote Sensing and GIS. A Methodological Consideration. 3rd FIG Regional Conference, Jakarta.

Schlünzen, K. H., Hoffmann, P., Rosenhagen, G., & Riecke, W. (2010). Long-term changes and regional differences in temperature and precipitation in the metropolitan area of Hamburg. *International Journal of Climatology*, *30*(8), 1121–1136. https://doi.org/10.1002/joc.1968

Sclar, E. D., Garau, P., & Carolini, G. (2005). The 21st century health challenge of slums and cities. *Lancet*. https://doi.org/10.1016/S0140-6736 (05)71049-7

SECR (State of Ethiopian Cities Report). 2015: A report of Ethiopian Cities 2015: Unpublished Ministry of Urban Development, Housing and Construction (MUDHCo) and Ethiopian Civil Service University (ECSU) .

SEI (Stockholm Environment Institute). 2007: WEAP, Water Evaluation and Planning System users guide. Stockholm Environment Institute Boston, USA.

SEI (Stockholm Environmental Institute). 2013: WEAP (Water Evaluation and Planning) system. Software, Stockholm Environmental Institute (SEI).http://www.weap21.org/

SEI (Stockholm Environmental Institute). 2014: WEAP Tutorial A collection of stand-alone modules to aid in learning. Stockholm Environmental Institute (SEI). http://www.weap21.org/downloads/GWC_Report_4.pdf

Semenov, M. a, & Barrow, E. M. (2002). A Stochastic Weather Generator for Use in Climate Impact Studies. User Manual, Hertfordshire, UK, (August), 0–27.

Shackley, S. (2001): Epistemic lifestyles in climate change modeling In: Changing the Atmosphere: Expert Knowledge and Environmental Governance.Miller CA, Edwards PN, eds. Cambridge: MIT. 107–134.

Shishegar, N. (2014). The impact of green areas on mitigating urban heat island effect: A review. *International Journal of Environmental Sustainability*, *9*(1), 119–130. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84899817103&partnerID=40&md5=b385cdeec8e8f0cd3bbfa8adf06bb679

Smagorinsky, J. (1963). General circulation experiments wiht the primitive equations I. The basic experiment. *Monthly Weather Review*, *91*(3), 99–164. https://doi.org/10.1126/science.27.693.594

Solomon, S., D., Qin, M., Manning, Z., Chen, M., Marquis, K. B., Averyt, M. T., … Miller. (2007). Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *New York Cambridge University Press*, 996. https://doi.org/10.1038/446727a

Solomon, S., Plattner, G.-K., Knutti, R., & Friedlingstein, P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(6), 1704–9. https://doi.org/10.1073/pnas.0812721106

Steeneveld, G. J., Koopmans, S., Heusinkveld, B. G., Van Hove, L. W. A., & Holtslag, A. A. M. (2011). Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *Journal of Geophysical Research Atmospheres*, *116*(20). https://doi.org/10.1029/2011JD015988

Stephen, F.; Adrian L. & Brian, M. (1998): Groundwater in Urban Development: Assessing Management Needs and Formulating Policy Strategies. World Bank, Washington DC, US.

Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*. https://doi.org/10.1002/joc.2141

Sundberg, M. (2007). Parameterizations as Boundary Objects on the Climate Arena. *Social Studies of Science*, *37*(3), 473–488. https://doi.org/10.1177/0306312706075330

Suomi, J. 2014: Characteristics of Urban Heat Island (UHI) In a High-Latitude Coastal City a Case Study of Turku, Finland. Annales Universitatis Turkuensis A II. 295, 11-21. ISBN: 978-951-29-5912-9

Tabari, H., De Troch, R., Giot, O., Hamdi, R., Termonia, P., Saeed, S., … Willems, P. (2016). Local impact analysis of climate change on precipitation extremes: Are high-resolution climate models needed for realistic simulations? *Hydrology and Earth System Sciences*, *20*(9), 3843–3857. https://doi.org/10.5194/hess-20-3843-2016

Taesombat, W., & Sriwongsitanon, N. (2009). Areal rainfall estimation using spatial interpolation techniques. *ScienceAsia*, *35*(3), 268–275. https://doi.org/10.2306/scienceasia1513-1874.2009.35.268

Taylor, K. E., Stouffer, R. J. & Meehl, G. A. 2012: A Summary of the CMIP5 Experiment Design (Program for Climate Model Diagnosis and Inter-comparison.93, 485-498. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Technology, C.-C. for N. (2010). The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits. *Proceedings of the Water Environment Federation*, 1–76. http://doi.org/10.2175/193864711802639741

Thoeun, H. C. (2015). Observed and projected changes in temperature and rainfall in Cambodia. *Weather and Climate Extremes*, *7*, 61–71. https://doi.org/10.1016/j.wace.2015.02.001

Tolon, U. W. (2008): Comparison of Urban Upgrading Projects on Development Cooperation in Ethiopia. Francesc Magrinyà Torner.

Tomassini, L., Reichert, P., Knutti, R., Stocker, T. F., & Borsuk, M. E. (2007). Robust Bayesian uncertainty analysis of climate system properties using Markov chain Monte Carlo methods. *Journal of Climate*, *20*(7), 1239–1254. https://doi.org/10.1175/JCLI4064.1

Toy, S., & Yilmaz, S. (2010). Evaluation of 10-Year Temperature Differences between Urban and Rural Areas of a Well-Planned, Unindustrialized, and Medium-Sized Turkish Town, Erzincan. *Journal of Urban Planning and Development-Asce*, *136*(4), 349–356. https://doi.org/10.1061/ (asce) up.1943-5444.0000022

Trenberth, K. E. (2013). El Niño Southern Oscillation (ENSO). In *Reference Module in Earth Systems and Environmental Sciences*. https://doi.org/10.1016/B978-0-12-409548-9.04082-3

Trzaska, S., & Schnarr, E. (2014). A review of downscaling methods for climate change projections. *United States Agency for International Development by Tetra Tech ARD*, (September), 1–42.

Tsidu, G. M. (2012). High-resolution monthly rainfall database for Ethiopia: Homogenization, reconstruction, and gridding. Journal of Climate, 25(24), 8422–8443. https://doi.org/10.1175/JCLI-D-12-00027.1

Tsidu, G. M. (2016a). Southern Africa between 5° and 30°S [in "State of the Climate in 2015"]. Bulletin of the American Meteorological Society, 97(8), S192-193. https://doi.org/10.1175/2016BAMSStateoftheClimate.1

Tisdu G. M. (2016b): Eastern Africa, state of Climate in 2015. Bulletin of the American Meteorological Society, 97 (8).

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., & Steininger, M. (2003). Remote sensing for biodiversity science and conservation. *Trends in Ecology and Evolution*. https://doi.org/10.1016/S0169-5347 (03)00070-3

Turral, H., Burke, J., Faures, J. M., & Faures, J. M. (2011). Climate change, water and food security. *Rome: Food and Agriculture Organization of the United Nations.*, 204.

UNEP. (2008). *Vital Water Graphics: An Overview of the State of the World's Fresh and Marine Waters*. *United Nations Environment Programme (UNEP)*. https://doi.org/92-807-2236-0

United Nations Department of Economic and Social Affairs (UNDESA). (2010). *World Urbanization Prospects: The 2009 Revision Highlights*. *New York* (Vol. ESA/P/WP/2). https://doi.org/10.2307/2808041

United Nations Department of Economic and Social Affairs (UNDESA). (2015). World Population Prospects - Population Division - United Nations. Retrieved from https://esa.un.org/unpd/wpp/

United Nations. (2010). *World Urbanization Prospects: The 2009 Revision*. *Population and Development Review* (Vol. ESA/P/WP/2). https://doi.org/10.2307/2808041

UN-Water. (2012). *WWDR4: Managing Water under Uncertainty and Risk*. *THE UNITED NATIONS WORLD WATER DEVELOPMENT REPORT 4* (Vol. 1)

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1), 5–31. https://doi.org/10.1007/s10584-011-0148-z

Várallyay, G. (2010). The impact of climate change on soils and on their water management. *Agronomy Research*, *8*(II), 385–396.

Veerbeek, W., Denekew, H., Pathirana, A., Brdjanovic, D., Zevenbergen, C., & Bacchin, T. (2011). Urban Growth Modeling to Predict the Changes in the Urban Microclimate and Urban Water Cycle. *... Conference on Urban ...*, 1–8. Retrieved from http://web.sbe.hw.ac.uk/staffprofiles/bdgsa/temp/12th ICUD/PDF/PAP005339.pdf

Vermote, E. F., El Saleous, N., Justice, C. O., Kaufman, Y. J., Privette, J. L., Remer, L., … Tanré, D. (1997). Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: Background, operational algorithm and validation. *Journal of Geophysical Research*, *102*(D14), 17131. https://doi.org/10.1029/97JD00201

Vörösmarty, C. J., Vo, C. J., & Green, P. (2009). Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science, 284*(2000), 284–288. https://doi.org/10.1126/science.289.5477.284

Wang, Y. 2015: Climate Change and Municipal Storm-water Systems. A white paper prepared for the Canadian Water Network research project. An Integrated Risk Management Framework for Municipal Water Systems. *School of Engineering at the University of Guelph Ontario, Canada.*

Wayne, G. P. (2013). The Beginner’s Guide to Representative Concentration Pathways (RCPs). *Skeptical Sciece*, *1.0*, 1–24.

Weart, S. (2007). RE: The discovery of global warming. *Isis; an International Review Devoted to the History of Science and Its Cultural Influences*, *98*(3), 611; discussion 611-612. https://doi.org/10.1029/2004eo280007

Weart, S. (2010). The development of general circulation models of climate. *STUDIES IN HISTORY AND PHILOSOPHY OF MODERN PHYSICS*, *41*(3, SI), 208–217. https://doi.org/10.1016/j.shpsb.2010.06.002

Werner, B. and Collins, R., 2012: Towards efficient use of water resources in Europe. European Environmental Agency (EEA), Report Vol. 1. Pp-74; ISSN 1725-9177; doi: 10.2800/95096

WHO. (2010). Urban planning, environment and health: from evidence to policy action. *World Health Organization, Regional Office for Europe*, 119. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0004/114448/E93987.pdf

WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation. (2012). *Progress on Drinking Water and Sanitation*. *Update*. https://doi.org/978-924-1503279

WHO/UNICEF. (2005). WHO 2004 Meeting the MDG Drinking Water and Sanitation Target: A Mid-Term Assessment of Progress. *UNICEF/WHO, Geneva, Switzerland*. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Meeting+the+MDG+drinking+water+and+sanitation+target:+a+mid-term+assessment+of+progress#0

Wilby, R. L. (2007). A review of climate change impacts on the built environment. *Built Environment*, *33*(1), 31–45. https://doi.org/doi:10.2148/benv.33.1.31

Wilby, R. L. (2008). Constructing climate change scenarios of urban heat island intensity and air quality. *Environment and Planning B: Planning and Design*, *35*(5), 902–919. https://doi.org/10.1068/b33066t

Wilby, R. L., & Perry, G. L. W. (2006). Climate change, biodiversity and the urban environment: a critical review based on London, UK. *Progress in Physical Geography*, *30*(1), 73–98. https://doi.org/10.1191/0309133306pp470ra

Wilby, R. L., Dawson, C. W., & Barrow, E. M. (2002). SDSM — a decision Support Tool for the Assessment of Regional Climate Change Impacts. *Environmental Modelling & Software*, *17*(2), 145–157. https://doi.org/10.1016/S1364-8152(01)00060-3

Wilhite, D. A. (2000). Drought as a natural hazard: Concepts and definitions. *Drought: A Global Assessment*, 3–18.

Williams, K. D., Senior, C. A., & Mitchell, J. F. B. (2001). Transient climate change in the Hadley Centre models: The role of physical processes. *Journal of Climate*, *14*(12), 2659–2674. https://doi.org/10.1175/1520-0442 (2001)014<2659:TCCITH>2.0.CO;2

WMO. (2008). Guide to Meteorological Instruments and Methods of observation. Guide to Meteorological Instruments and Methods of Observation (Vol. I & II). https://doi.org/Guide to meteorological instrument and observing practices

WMO. (2012). The Urban Observations. Guide to Meteorological Instruments and Methods of Observation. WMO- Geneva Switzerland, No. 8 Part II, Chapter 11. http://library.wmo.int/pmb_ged/wmo_8_en-2012.pdf

WMO. (2014). Weather and Water in Cities. WMO, World Metrological Organization, Geneva Switzerland. No. 853.

WMO. (2015): Statement of the status of the global climate in 2014. World Metrological Organization (*WMO)*, Geneva Switzerland, No. 1152.

WMO. (World Metrological Organization). 1996. Climatological Normals (CLINO) for the period 1961–1990*. World Meteorological Organization:* Geneva, Switzerland.

World Urbanization Prospect. (2014): Estimates of the urban and rural populations, percentage urban, and rate of urbanization. UN Population. www.unpopulation.org.

Wu, C., & Murray, A. T. (2003). Estimating impervious surface distribution by spectral mixture analysis. *Remote Sensing of Environment*, *84*(4), 493–505. https://doi.org/10.1016/S0034-4257 (02)00136-0

WWAP (2009). The United Nations World Water Development Report 3: Water in a Changing World. *World Water*. https://doi.org/10.1017/CBO9781107415324.004

Xian, G. & Crane, M. (2006). An analysis of urban thermal characteristics and associated land cover in Tampa Bay and Las Vegas using Landsat satellite data, *Remote Sensing of Environment* 104 (2006), pp. 147–156

Xian, G., Crane, M., & Mcmahon, C. (2008). Quantifying Multi-temporal Urban Development Characteristics in Las Vegas from Landsat and ASTER Data. *Photogrammetric Engineering & Remote Sensing*, *74*(4), 473–481. https://doi.org/10.14358/PERS.74.4.473

Yahaya, O., Rodiya, A.A., Nathaniel, E.& Micheal, O. (2014): Simulation And Modeling of Climate Change Effects On River Awara Flow Discharge Using WEAP Model For Effective Water Management. International Journal of Technology Enhancements And Emerging Engineering Research. 2 (7). ISSN 2347-4289.

Zhang, Y. (2011). Urban Open Space Design For The Chinese Floating Population Community: Planning And Site Design Guidelines. Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Master of Landscape Architecture.

Zhou, L., Dickinson, R. E., Tian, Y., Fang, J., Li, Q., Kaufmann, R. K., … Myneni, R. B. (2004). Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences*, *101*(26), 9540–9544. https://doi.org/10.1073/pnas.0400357101

Zhou, Q. (2014). A Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts. *Water*, *6*(4), 976–992. https://doi.org/10.3390/w6040976

Zhu, R. 2009: China's South-North Water Transfer Project and Its Impacts on Economic and Social Development. Management Bureau of South-North Water Transfer Planning and Design. Ministry of Water Resources of China. http://www.mwr.gov.cn/english1?20060110104100XDENTE.pdf.

Zhu, T., Melamed, M., Parrish, D., Gauss, M., Klenner, G. L., Konare, A., & Liousse, C. (2012). *WMO/IGAC impacts of megacities on air pollution and climate*. *Urban Climate* (Vol. 41). https://doi.org/10.1016/j.uclim.2012.10.004

Ziv, J. C. & Cox, W. 2007: Mega cities and Affluence: Transport & Land Use Considerations; Conservatoire National des Arts et Metiers, Paris. http://www.publicpurpose.com/ut-wctrs2007.pdf